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JANUARY TO JUNE 24, 1914

VOL. XXXIII, PART I

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33 WEST THIRTY-NINTH STREET
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SOURCES OF DIRECT CURRENT FOR ELECTROCHEMICAL PROCESSES

BY F. D. NEWBURY

ABSTRACT OF PAPER

The problem involved in producing direct current for electrochemical processes is outlined, and the difficulties are pointed out.

Of the methods of power supply using steam turbines that are available, it is shown that:

(a) Direct-connected d-c. turbo-generators are available only in relatively small units, and cannot be designed as conservatively from the commutation standpoint as is desirable.

(d) Unipolar generators driven by turbines have proved unsatisfactory on account of current collection difficulties.

(c) The standard medium-speed d-c. generator connected to a high-speed turbine through gearing affords a satisfactory unit.

(d) The combined a-c. turbo-generator and converter unit probably affords the best all-around method. It is economical, reliable and flexible. Its particular fields of application are where large units and long transmissions are required.

In waterpower plants, direct-connected d-c. generators and a-c. generators with converters are available. The combined a-c.-d-c. equipment is usually the most reliable and economical.

With reciprocating engine units, there is no reason for considering other methods than the direct-connected slow-speed generator.

THE ELECTRICAL power problem involved in all commercially important electrochemical processes is the production of very large amounts of direct-current energy at comparatively low voltages. Single circuits often require as much as 10,000 amperes, and in electrolytic processes the voltage is rarely more than 250 volts. The present paper will briefly outline the problem, list the various methods of obtaining the required electrical energy and compare these methods from the standpoints of efficiency, first cost and reliability in operation.

The electrical problem is intimately connected with the available prime movers and their advantageous operating speeds. In modern installations, steam turbines and waterwheels with their relatively high speeds are of major importance. Reciprocating steam engines are of importance mainly in combination with low-pressure turbines. Up to the present time, gas and oil engines have had little or no application in modern electrochemical plants, but the present rapid development of

the Diesel engine abroad may make its influence felt in the near future.

The design of direct-current machinery, either generators or synchronous converters, of sufficient current capacity for electrochemical work, is a problem of considerable inherent difficulty because of the large currents involved, the high speeds of the preferred prime movers, and the continuous full-load service required. In some cases, as in a.c. turbo-generators, the low voltage involved may become a serious limitation in design aside from its association with the large amperage.

The large currents and high speeds are closely associated and may be discussed together as the commutation problem.

The Commutation Problem.

In direct-current generators and synchronous converters the *speed* and the permissible *number of poles* bear a certain relationship, the product of which, in terms of revolutions per second and pairs of poles, is the *frequency*. In synchronous converters this is, of course, a rigid relationship, due to their synchronous operation. In direct-current generators, the frequency is commonly lost sight of, but at the higher outputs and higher speeds under consideration it is practically as important a limitation as in synchronous converters. The *current output* in commutating machines is proportional to the number of parallel circuits in the armature, which in turn is equal to the number of poles. The tendency, therefore, is to increase the number of poles indefinitely as the required current output is increased. But this indefinite increase is limited, to mention only the most important factors, by the number of current-collecting brush arms that can be placed around the commutator and the number of commutator bars that can be placed between brushes without exceeding safe commutator peripheral speeds. If conservative design limits are not to be exceeded, it is necessary to keep the frequency within 60 cycles and desirable to keep it within 50 cycles.

With the maximum number of parallel circuits and poles that can be used, the total current output is then limited by the permissible length of commutator. At the higher commutator speeds required by the frequencies usual with the d-c. generators under consideration, 800 amperes per brush arm is as high as should be considered under the continuous service required by electrochemical processes. Lower values are commonly used in

60-cycle synchronous converters and higher values are permissible in 25-cycle converters, the peripheral speeds being respectively higher and lower. Uniformly higher values can be safely used for the intermittent service commonly experienced in industrial plants and central stations. Higher values can also be used in very low voltage machines using metal instead of carbon brushes.

With these none too conservative limits of 50 cycles and 800 amperes per brush arm, the following maximum current outputs result, for 250-volt direct-current generators, for the range of speeds commonly used:

Prime mover and generator speed	Poles	Frequency	Amperes	Kw. at 250 volts
1,800–1,500	4	60–50	1,600	400
500	12	50	4,800	1,200
400	16	53	6,400	1,600
300	20	50	8,000	2,000
250	24	50	9,600	2,400
200	30	50	12,000	3,000
175	34	50	13,600	3,400
150	40	50	16,000	4,000

Larger outputs than those listed have in some instances been built at certain speeds but only at the expense of reliability in operation. This is particularly true of direct-connected direct-current turbo-generators.

Double-commutator generators if used would double the above ampere and kilowatt limits, but difficulties inherent in parallel operation of the circuits from two commutators connected to the same winding have, after several unfortunate attempts, caused this construction to be abandoned for large machines where conservative practise has been followed.

It is evident from the above discussion that the major difficulties in building generators and synchronous converters for large currents center in the mechanical design of the commutator. The peripheral speed is pushed to the highest limit to obtain room for as many poles as possible; the length of commutator face is made as long as possible to increase the permissible current per circuit to the limit.

Three constructions have been developed and are in more or less general use to meet these severe conditions.

(a) A modification of the ordinary V-ring construction involving an additional auxiliary V-ring at the outer end of the commutator.

(b) A modification of the ordinary V-ring construction involving a shrink midway between the two ends of the commutator bars.

(c) A simple shrink ring construction involving more shrink rings, depending on the length of the commutator.

The so-called three V-ring type retains all the advantages from the repair standpoint of the simpler two V-ring type. The combined V-ring shrink ring type has the disadvantages from a repair standpoint inherent in the simple shrink type. These two types are comparable in their range of application. Such commutators have been built with 20 to 25-in. (50.8 to 63.5-cm.) face and 5500 ft. (1676 m.) per minute peripheral speed. The simple shrink ring type obviously does not permit of easy repair and is limited to comparatively small commutator diameters. It is, however, the strongest construction available for smaller diameter commutators and is necessarily used for direct-connected turbo units.

Improvements in commutator design and construction during the past four or five years have been largely instrumental in improving the operation and extending the permissible output of the generators and synchronous converters under consideration.

A word in regard to the operation of machines having long high-speed commutators is not out of place. Such commutators built up in part, as they are, of more or less compressible insulating material, require a period of "seasoning" and adjustment before they will operate without further change in shape. A certain amount of such seasoning occurs during the manufacture and test of the machine (where testing is possible), but it is very seldom that additional grinding and tightening is not necessary after installation.

The Distribution Problem

Energy in the form of heavy currents at comparatively low voltages as used in electrochemical work is not efficiently portable. It must be used substantially where it is generated. Very heavy busbar structures, expensive both in first cost and in energy loss, are necessary to carry the large current involved, from the generator to the point at which it is used, and for distances more than a few hundred feet the cost becomes prohibitive. For transmission distances of 1000 ft. (304.8 m.) or more, it is usually necessary to consider transmission at a higher voltage. This introduces the alternating-current gen-

erator and synchronous converter combination of power supply. The relative location of power station and the pots or tanks where the current is used has, therefore, an important bearing on the choice of a power system. This will be referred to again in detail in discussing water power installations.

Voltage Variation

Electrochemical plants usually require some means of adjustment of the voltage in order to maintain constant current under the varying circuit conditions incident to operation. With direct-current generators this is readily obtained by simple field current control, a single generator usually supplying a single series of tanks. With synchronous converters, if the required range is not more than 5 per cent, it can also be obtained by adjustment of the field current, assuming sufficient reactance to exist in the alternating-current circuit. If a greater range of voltage variation is required, several methods are available, the one commonly preferred at the present time involving the addition of a small alternating-current generator to the synchronous converter unit, this generator acting as a synchronous booster. In both generators and converters, the performance under the wide range of voltage sometimes required has been greatly improved, in recent designs, by properly proportioned commutating poles.

Continuity of Service

A feature of electrochemical load that has an important bearing on the satisfactory performance of the equipment is the requirement for steady full-load operation for long periods without shutdown. Many commutating machines that will operate with entire satisfaction on a fluctuating railway or lighting load will fail utterly on a continuous load of no greater value than the average load in the former case. The fluctuating load affords periods of light load during which the commutator and brushes can clean and polish themselves and the daily shutdowns permit the correction of incipient troubles. It is for this reason more than any other that serious trouble has been experienced in so many instances with commutating machines in electrochemical plants. For this reason alone, commutating machines intended for operation in such plants should be of the most substantial and of the simplest type and should be designed, particularly from the standpoint of commutation, well within conservative limits.

The general problem having been stated, the various methods of meeting the required conditions will be considered.

Steam Turbine-Driven Units

Four arrangements involving steam turbine prime movers have been more or less successfully operated:

(a) Direct-connected commutator-type direct-current generators.

(b) Direct-connected unipolar-type direct-current generators.

(c) Gear-connected commutator-type direct-current generators.

(d) Direct-connected alternating-current generator with synchronous converter.

(*a*) Direct-connected, direct-current turbo-generators are limited to relatively small current ratings, due to the very high speed necessary if reasonable turbine economy is to be obtained, and for such sizes as can be built, suitable for electrochemical work, conservative design limits must be exceeded. For this reason it is almost impossible to build direct-connected units that will be generally satisfactory under the severe operating conditions inherent in electrochemical works. The efficiency of the direct-current turbo-generator is low due to the high speed and frequency; that of the turbine is low, due to the speed which, while high from the standpoint of the generator, is low from the standpoint of best turbine performance. The trend of development, both in this country and in Europe, where the most work with direct-connected direct-current units has been done, is away from direct-connected units.

(*b*) Since the difficulties in the design of direct-current generators for electrochemical work have been mainly associated with the commutator, a generator from which commutation has been eliminated would seem to offer a way out of all troubles. In the unipolar type, commutation is eliminated by the employment of unipolar flux, that is, flux of one polarity external to the armature. It is only necessary to collect the generated direct current from the two ends of the armature by means of collector rings and brushes as commonly employed in alternating-current generators and synchronous converters. But it has required only two or three attempts with large units to show that, with the increase in current and speed desired, the simple process of current collection becomes a more difficult problem

than commutation at the lower speeds available with alternative methods. The only unipolar generator large enough to be considered for electrochemical power supply now in commercial operation is the 2000-kilowatt, 250-volt, 8000-ampere, 1200-rev. per min. unit described in a paper before this Institute.* This paper also gives in detail the difficulties encountered and overcome before this unit could be operated with reasonable maintenance cost. Due to the low core loss and windage loss of this type, the efficiency is relatively high. The first cost and maintenance cost, however, are also high.

(*c*) With the development, during the past three years, of a satisfactory gear for the transmission of large powers, the direct production of large currents with steam turbine prime movers has been placed on a much more satisfactory footing. This gearing is usually of the double helical type with the pinion mounted in a floating frame so as to equalize the tooth pressures, in spite of the long face necessary. Obviously, with an efficient and satisfactory gear available, the speeds of the turbine and the generator can be selected within fairly wide limits to suit the conflicting requirements of the prime mover and generator. As a matter of fact, generators which have been supplied for connection to turbines through gearing have been of the same speed and design as generators of the same rating driven by induction or synchronous motors in motor-generator sets. For example, such ratings for 250 volts would be 1000 kilowatts at 500 rev. per min., 1500 kilowatts at 360 rev. per min.; 2000 kilowatts at 300 rev. per min., and 3000 kilowatts at 180 rev. per min., which are all within the limiting ratings and speeds previously given. These units may, therefore, be designed as conservatively as similar generators used in motor-generator sets with relatively high efficiency and low cost. Such units have been in service for several years and have amply proved their dependability. Two large units of 3750 kilowatts, the turbine operating at 1800 rev. per min., and the generator at 180 rev. per min., have been supplied for lighting service.

(*d*) Another satisfactory means for obtaining the required direct current is afforded by turbine-driven alternating-current generators to which synchronous converters are electrically connected. The alternating-current generators may be of the usual synchronous type or of the induction type. This method has been used in a number of copper refining plants, and was

* *Development of a Successful Direct-Current* 2000-*kw. Unipolar Generator*, B. G. Lamme, TRANSACTIONS *A. I. E. E.*, Vol. XXXI, p. 1811.

used in industrial plants generally prior to the development of the geared unit. While it is lower in cost than either the direct-connected or unipolar types of generators and higher in efficiency than the former, it is somewhat inferior to the gear-connected unit, except when the unit becomes so large that 3600 rev. per min. turbines cannot be used in the geared unit. This method possesses obvious advantages in flexibility of plant arrangement. For plants in which the transmission distance is short enough, the generator can be designed for the required converter voltage and the converter connected directly to the generator terminals. Where, however, distances are greater, the generator can be wound for a higher voltage and step-down transformers installed with the converters at the electrolytic tanks.

Synchronous converters have been used instead of motor-generator sets primarily because of their higher efficiency. Considering the most unfavorable conditions from the standpoint of the synchronous converter, that is, a 60-cycle synchronous booster converter with transformers, the efficiency of a 1000-kilowatt, 250-volt, synchronous converter outfit would be at least 92 per cent, while the efficiency of an equivalent motor-generator set without transformers would rarely be higher than 88 per cent. Without transformers, without the boosters (where large variations in voltage are not required) and with a 25-cycle system, the comparison would be still more favorable to the synchronous converter.

If it is necessary to entirely separate, electrically, the different circuits, each consisting of a synchronous converter and series of tanks, this can be done as effectively by the use of transformers in connection with the converters as by the use of separate generators in motor-generator sets.

If transformers are necessary, the combined cost of the converter and transformer will be substantially the same as that of the motor-generator set.

The inherent advantages of the induction type generator for this service have been pointed out in a paper before the Institute,* in which a specific application to electrolytic work was described. The stators of the synchronous and induction generators are substantially the same; the difference between them lies in the rotors. The rotor of the induction generator consists of a simple winding formed of bars short-circuited by end rings as in the more familiar induction motor. As in the

*The Non-Synchronous Generator in Central Station and Other Work, W. L. Waters, TRANSACTIONS A. I. E. E., Vol. XXVII, 1908, p. 157.

motor, this winding need not be insulated from the core, and there are no collector rings and brushes which, at turbine speeds, require some care and attention. While, however, the induction type rotor is inherently simpler than the synchronous generator rotor, so much more development work has been done with the latter type that, as actually constructed, the synchronous rotor is, if anything, more reliable in operation than the rotor of the induction generator. The exciting or magnetizing current of the induction generator must be supplied from the synchronous converter so that the converter is under the handicap of operation at a power factor lower than unity. This handicap may become serious if it is desired to increase the voltage above that originally contemplated. The voltage of the synchronous generator on the other hand is very simply controlled by changes in its exciting current, so that in this respect the combined alternating-current generator-synchronous converter unit is on a par with the direct-current generator. For these reasons the induction generator has not been extensively applied.

The comparative efficiency of the various methods just described, based on a 2000-kilowatt, 250-volt unit, are given in the following table:

	Apparatus	Efficiency
(a)	Direct-connected commutator type generator, three 750-kilowatt, 1500 rev. per min.	89
(b)	Direct-connected unipolar type generator, 2000-kilowatt, 12,000 rev. per min.	92
(c)	Gear-connected generator,	
	Gear 3,600-300 rev. per min.	98
	Generator 2,000 kilowatts, 300 rev. per min.	93.5
	Combined	91.6
(d)	Alternating-current generator-converter set	
	A-c. generator, 2,000 kilowatts, 3,600 rev. per min.	94.5
	Cables	99.5
	Synchronous converter, 2,000 kilowatts, 360 rev. per min.	96
	Combined	90.2

In considering these efficiencies, the lower economies of the lower speed turbines for (*a*) and (*b*), and for (*c*) in larger sizes, should not be lost sight of.

Waterwheel-driven Units

With waterwheel-driven units, the choice lies between direct-connected direct-current generators or direct-connected alternating-current generators and synchronous converters. In very few plants can waterwheel generators be located near enough to the electrochemical plant to justify the installation of direct-connected *direct-current* generators, in view of the

expensive structure required for the transmission of the heavy currents. The various questions involved in such an installation can best be brought out by a comparison of the d-c. and a-c.-d-c. installations in a specific instance.

For this purpose a plant having an ultimate capacity of 120,000 h.p. with a water power having a 250-ft. (76.2-m.) head has been chosen. The largest direct-current units that could be even considered are 5000-kilowatt, 250-volt, operating at a speed of 170 rev. per min. It will be noted that this current rating in proportion to the speed is higher than previously given as a conservative rating. Nineteen such units would be required and with a diameter of approximately 25 ft. (7.6 m.) these generators would require a power house approximately 700 ft. (213.3 m.) long. Contrasted with the direct-current equipment, eight 12,500-kv-a., 277 rev. per min. 60-cycle generators could be used. These generators could be placed in a power house approximately 250 ft. (76 m.) long. In each case one spare unit is included. In further contrast with the direct-current units, the alternating-current units are well within conservative design limits, much larger generators at higher speeds having been built. With the direct-current units a lower speed has necessarily been chosen than would be most economical for the water wheels, consequently the water wheel efficiencies are lower for the direct-current plant than for the alternating-current plant. The comparative efficiencies with the two systems are shown in the following table:

COMPARATIVE EFFICIENCIES.

	D-C. generation	A-C. generation and converters
Waterwheels	80 per cent	89 per cent
Generators	95	96
Transmission, assuming a distance of 2000 ft. (609 m.)	92	99.5
Step-down transformers		98.6
Synchronous converters		96
Low-tension wiring from step-down transformers to load (assuming 50 ft. 15.2 m.)		99.6
Over-all efficiencies (from water to load)	69.7	80.1

Ten per cent difference in efficiency would mean an appreciable difference in the investment cost and, therefore, in the cost of power, even with a water power installation. In the present instance, assuming an investment cost of $60 per h.p., this difference would amount to three-quarters of a million dollars.

The comparative costs of the two propositions, based on the total cost of the direct-current system as 100 per cent, are shown in the following table:

	D-C. generation	A-C. generation and converters
19 5,000-kilowatt 170-rev. per min. 250-volt d-c. generators with water wheels complete (one unit spare) approx.	60 per cent	
8 12,750-kilowatt 277 rev. per min., 11,000-volt 60-cycle a-c. generators with waterwheels complete (one unit a spare) approx.		38 per cent
Transmission [based on 90,000 kilowatts 250 volts for 2,000 ft. (609 m.) with copper at 10 ½ cts. per lb. (0.45 kg.) loss 8 per cent] approx.	38	1
19 5250-kilowatt, three-phase, 60-cycle O. I. W. C. transformers 11,000 to 180 volts (one a spare unit) approx.		4½
19 5,000-kilowatts, six-phase, 250-volt d-c. synchronous converters with 10 per cent buck and 10 per cent boost (one a spare unit) approx., (Each unit consisting of two 2500-kilowatt converters)		29
Low-tension wiring from step-down transformers to load [50 ft. (15.2m.) assumed] approx.		1
Switching equipment, approx.	2	7½
Totals	100	81

The above costs do not include the cost of supports, anchors and insulation for the direct-current transmission line which, with the very heavy structure necessary, would be a considerable item.

Obviously with a smaller plant and, particularly, with a shorter transmission distance, the cost of the direct-current plant would be materially less. The efficiency, however, would not be greatly improved unless more efficient wheels could be used, and the drop in the transmission reduced by a material increase in the cost of this part of the plant. For example, for a plant of 60,000 h.p. instead of 120,000 h.p. and assuming 1000 ft. (304.8 m.) length and 5 per cent loss for the direct-current transmission, the a-c.-d-c. plant would still have 8 per cent higher efficiency but its cost would be 10 per cent more than the direct current. Even on this basis the a-c.-d-c. plant would be more economical. Its flexibility is, moreover, an additional advantage of great importance.

These figures are well substantiated by the change in practise

found desirable by one of the largest aluminum companies. All of the recent work done by this company has been with alternating-current generators and synchronous converters. A large installation involving nine 2500-kilowatt, 500-volt, 60-cycle synchronous converters is now being erected and a still larger installation involving 60-cycle machines of similar rating is in process of construction.

At the lower voltages more commonly involved in electrochemical work, a 60-cycle system has considerable advantage over a 25-cycle system. The higher frequency is an advantage from the standpoint of the turbine because of the higher available speeds; costs throughout the installation are less. In the synchronous converters the higher frequency is an advantage due to the larger number of poles and armature circuits for a given speed. At the higher voltages, that is, 500 to 700, sometimes used for the reduction of aluminum, there is a slight advantage, from the standpoint of the synchronous converter design, in the lower frequency. This, however, is not sufficient to overcome the other disadvantages incident to the lower frequency.

Reciprocating Engine Units

While these units have very little application in modern plants, they should be mentioned to complete this survey. From the generator standpoint the lower speeds common with reciprocating units is a decided advantage, permitting as it does a large number of poles and armature circuits. On account of this fact there is no reason for considering other schemes than the simple direct-connected commutator-type direct-current generator. The efficiency of a 2000-kilowatt, 250-volt unit would be 94 per cent.

Conclusion

From the many schemes proposed for the generation of direct current for electrochemical plants, two plans assuming steam turbine prime movers have decided advantages in efficiency and reliability and flexibility in operation. These are the gear-driven commutator-type generator where the distance between the power plant and the place of utilization is short and the combined alternating-current generator and synchronous converter plant when this distance becomes too great for economical low-voltage transmission or the units become too large for economical turbine speeds.

DISCUSSION ON "SOURCES OF POWER FOR ELECTROCHEMICAL PROCESSES" (NEWBURY), NEW YORK, JANUARY 9, 1914.*

G. A. Roush: Mr. Newbury takes up a standard outfit, with a capacity of 120,000 h.p., and draws comparisons on that basis. I think it would have been, possibly, of more value to the people interested in the electrochemical utilization, to have used for examples sizes of installations that are more nearly those that are actually in use, that is, as Mr. Addicks stated in his paper, in the neighborhood of 1000 to 1500 kw.

F. A. Lidbury: In only one line of electrolytic industry—the reduction of aluminum—are single installations of 120,000 h.p. conceivable at the present time; indeed, there is no other single line of electrolytic manufacture, the power requirements of which throughout the United States exceed 100,000 h.p., and the instance of water power generation examined by Mr. Newbury is so far removed from anything approaching what is possible in the refining of copper and the other metals, that his analysis has practically no bearing. Most electrolytic plants of importance, the aluminum industry being excluded, will be found to have a power consumption somewhere between 1000 h.p. and 10,000 h.p., and so far from single units of 5000 kw. being common, any plant which is consuming 5000 kw. will be found to be, even today, a considerable factor in its particular line of manufacture. Even in the largest electrolytic installations (still excepting aluminum plants) the size of units does not often exceed 1000 kw. Most electrochemists would, therefore, have been more interested in comparisons made between installations of units of capacities of this order than in those with which Mr. Newbury specifically dealt in considering water power generation. That the results of such a comparison would have been very different is clear from a consideration of his own data; it will no longer be correct to say that "in very few plants can water-wheel generators be located near enough to the electrochemical plant to justify the installation of direct-current generators." It is obviously true that where transportation or other conditions demand the location of the electrolytic plant at a considerable distance from the power house, d-c. generation will be out of the question in any case, but where no such condition is involved, it will usually be found not only feasible but the only rational scheme.

Having somewhat modified our starting point in regard to the size of unit which should be taken as typifying electrolytic

*At this joint meeting two other papers were presented, "(1) "Limitations of the Problem of Electrolytic Deposition," by Lawrence Addicks, of the American Electrochemical Society, and (2) "The Power Problem in the Electrolytic Disposition of Metals," by H. E. Longwell, of the American Society of Mechanical Engineers. These papers are published by the societies mentioned and not by the A. I. E. E.

requirements, Mr. Newbury's table connecting the prime mover and generator speed with the conservatively practicable capacity of units assumes quite another aspect; it teaches us that d-c. generators of 1000 kw. capacity can be directly connected to waterwheels of speeds as high as 600, if a voltage of 250 is used, and as high as 300 in the extreme case of voltage requirements as low as 125. Obviously, under typical conditions, there ceases to be any difficulty in d-c. generation in connection with any waterwheel speed that is likely to be met with. This, in turn, puts quite a different aspect upon the comparative efficiency of d-c. generation and a-c. generation with converters, as is obvious from the fact that the bulk of the difference in over-all efficiencies from water to load in Mr. Newbury's table is accounted for by the necessity of adopting, under the conditions which he examines, a turbine of lower speed and of 9 per cent lower efficiency for connection to the d-c. generator. Under conditions more truly typical, this necessity vanishes. It will usually be found advisable under these conditions to require no modification of waterwheel speed to accommodate either alternator or d-c. generator, as there will be no difficulty in obtaining either machine to give first-rate performance at the speed most advantageous from the point of view of waterwheel design. As a general rule it will be found much easier to get the electrical manufacturer than the turbine maker to make what compromises are necessary without appreciable loss of efficiency. There will, in any case, be but a slight difference in efficiency of a-c. and d-c. generators, probably not exceeding one per cent, and while there may be a considerable difference in cost between d-c. and a-c. units, the magnitude of this will depend upon a number of conditions, chief of which is the d-c. voltage; under favorable conditions, *e. g.*, where d-c. voltages approaching or exceeding 250 can be used, the cost of a-c. accessories (exciters, switching equipment, etc.) will go far towards completely wiping out this difference. In most cases, therefore, it is practically a question of determining the distance to which the value of the synchronous converter set with transformers and accessories, and including building space and investment in copper, will enable the current to be carried with the same per cent energy loss as that involved in transformation by the synchronous converter set; and perhaps it would be only in accord with experience to carry out this calculation with a healthy skepticism as to whether the over-all efficiency of a-c. generation and converters as expressed by the product of the efficiencies of the component parts of the system under test conditions will not be appreciably reduced under conditions of actual operation. Viewed from this standpoint, the radius of economic transmission of low-tension direct current will often figure out surprisingly large, and will, in almost every instance in which it is not necessary to place the load at a point determined by other considerations,

usually be sufficient to include not only a possible point of delivery to the load, but also the whole of the load-absorbing portion of the plant, within its area.

Economically, at least, two other points are to be considered. It is obvious that direct operating cost (*e.g.* attendance, oil, etc.) will in some respects be practically doubled by the necessity of maintaining two stations containing moving machinery, instead of one; and maintenance charges will also be considerably increased, though possibly not to the same extent. The smaller the installation, the more important this point becomes. Secondly, due weight must be given to the difference in depreciation on the same sum invested, respectively, in copper conductors and in synchronous converter equipment. This difference would be likely to appear more clearly at the end of a number of years' running than in the early stages of the installation. One cannot, of course, prophesy what the scrap price of copper is likely to be in 10 or 15 years time, but one has a pretty good idea of what the scrap price of a synchronous converter equipment of that age is likely to be. Both these factors have to be included in any proper scheme of economy, and they are not by any means insignificant in magnitude.

Lastly, the electrochemical engineer is also apt to have a prejudice in favor of simplicity. What he wants in the way of power equipment is something which will be primarily characterized by smoothness, ease and reliability in operation, and he is apt to know by experience that this is not most likely to be obtained by multiplying the electrical links in his chain of power machinery, or the number of points needing continual attention to insure the best operating results.

I frankly concede that these remarks do not apply to water power installations of such magnitude as Mr. Newbury deals with, and I also concede that he has pointed out that the validity of his conclusions decreases with decrease of unit capacity. It seemed highly desirable, however, that this portion of the subject should be discussed in its bearing upon the vast majority of electrolytic installations.

F. L. Antisell: It seems that one point which has been overlooked is the efficiency of partial loads. The reciprocating engine is capable of having the characteristic of the 100 per cent load, by varying the speed of the engine, tending to uniform mean effective pressure. In the various types of turbines, when we come to running at partial loads, we find a great falling off in efficiency. I do not think this point has been brought out fully, and it is a very important point in connection with this subject.

J. B. F. Herreshoff: Our system at first apparently required small units, and those were supplied with high-speed triple-expansion engines of the torpedo type. They were first installed about 15 years ago, in units of about 400 kw., making 350 rev. per min., operated condensing. Those were after-

wards operated with a low-pressure turbine. The engines gave very satisfactory results, but the cost of maintenance on a great many units is an item that we have to avoid. The first of the turbo-generators that we had was the first one of the Parsons type made in the United States, running about 5000 to 6000 rev. per min., generating direct current, and it had very long commutators. After that we put in an acyclic generator of 2000 kw., but we had trouble with the collectors. We found an enormous amount of heat going away from the machines, and inasmuch as it came out of four or five holes, it was a simple problem to take the temperature of the ingoing and outgoing air. We found that 30 per cent of the energy was going off in heat.

We also felt there must have been some mistake in the method heretofore used in arriving at the efficiency of this machine, which was supposed to run up to ninety-five per cent, but this method of getting at the efficiency seemed to be a pretty good one.

The next problem was how to get the best arrangement for making an alternating current, starting first with the steam turbine. Mr. J. B. Herreshoff conceived the idea of an alternating-current generator of a low voltage, connected without any transformer to a properly designed synchronous converter. A good many of these outfits have been built and they seem to have special advantages for this type of work.

J. B. Herreshoff: In an electrolytic plant, if you double the amperes you will deposit your copper in half the time. This will take double the voltage, and the result would be you would have four times the power in your tanks. There are some advantages in doing this. The temperature of the electrolyte would be kept up, and in some cases it might not be necessary to use steam. This is done at Great Falls. At that plant I believe they use a current density of about 40 amperes per sq. ft. (0.09 sq. m.), and the temperature of the electrolyte there is 150 deg. fahr. In the multiple system, the temperature will vary generally in the East here from 130 to 135 deg. fahr. The cost of keeping the electrolyte warm is so great that the temperature can not very well be kept higher.

It is interesting to note that if we do double the current density, although the power goes up four times, the cost per pound of copper only doubles. The objection to doing this, we have found, is that the deposits are not so smooth; they are apt to be crystalline, more brittle, which is often a very serious matter in the handling of the cathodes.

Mr. Newbury mentioned that it was very easy to vary the voltage, where there was only one synchronous converter connected with one alternator, by varying the field of the alternator. This is true. It can also be varied, to some extent, by varying the length of the synchronous converter, which has the effect of changing the power factor. Where two con-

verters are connected to one alternator, differences of voltage can be obtained by weakening the field of one slightly, and strengthening the field of the other. The advantage of doing this is that you can use a larger turbine and alternator, which, of course, means a little more cost in installation, but it also means a little better economy. The objection to this method of control is that on account of the power factor not being unity, the converter will heat up in some parts of the armature, but not seriously, if the difference of voltage between the converters is not more than thirty or forty.

C. O. Mailloux: The statement which has been made that the character of the copper deposit depends upon the current density requires some qualification. That it is true in cases such as those which have been referred to is due to the peculiar circumstances and conditions of the cases. It is not true as a general proposition, and the wide-spread belief that a regular deposit of ductile copper of good quality can be obtained only with low current-densities is quite erroneous. The quality of the copper deposited at the cathode may be independent of the current-density within very wide limits. It is possible to obtain very good deposits (and also very bad deposits) at any current-density between 10 and 1000 amperes per sq. ft. (0.09 sq. m.). A current-density of 1000 amperes per sq. ft. will doubtless seem enormous to those who are familiar only with the current-densities employed in electrolytic copper refining, which seldom exceed 30 amperes per sq. ft.; but it is true, nevertheless, that copper-deposits of the finest quality can be obtained at that high current-density. In 1885, I was called upon to develop a process of rapid electrotyping. Electrolytic copper "shells" such as used for making ordinary electrotypes have a thickness ranging from 0.010 to 0.015 inch (0.25 to 0.38 mm.). This means a weight ranging between 0.45 and 0.70 lb. per sq. ft., and the quantity of current required to deposit that amount of copper, allowing for some loss in current-efficiency, *i.e.*, allowing for electrolytic action which causes the deposit of something else besides copper—hydrogen, for instance—at the cathode, will range between 200 and 300 ampere-hours per sq. ft. With a current-density of only 10 amperes per sq. ft., the time required will therefore be from 20 to 30 hours. The problem which I was called upon to solve was to shorten the time to not over two hours. It was important that the copper shells should be very uniform in thickness, free from "pin-holes", and of the very best quality of copper. Considering their large size—that of a newspaper page—it seemed difficult to meet these requirements. It proved possible, however, to obtain deposits of the finest quality and uniformity with current-densities as high as 1000 amperes per sq. ft. This enabled the time to be cut down to less than one-half hour for a shell of full thickness; but for the purpose in view a rate of deposit producing a shell in one hour was sufficient and was adopted in practise.

These results were not mere laboratory experiments. The process was in regular operation for many months, turning out several hundred pounds of electrotype shells every day, and the number of shells found defective was surprisingly small. The secret was simple enough; it was merely a question of ***keeping the electrolyte under control***, so as to maintain it in substantially the same chemical, electrical and physical condition all the time. The amounts of copper sulphate and free acid in the electrolyte, the density, specific resistance, and temperature of the electrolyte, were all maintained within certain limits; and the electrolyte was systematically agitated and circulated. The object in view was, of course, to put the electrolyte in the best possible condition to meet the urgent demand for "ions" resulting from the high current densities. If there is not enough copper in solution at the cathode to satisfy the "cation" requirements of the current, the deficiency will be made up by a partial deposit of hydrogen with the copper; and it is well known that a very small proportion of hydrogen is sufficient to alter the quality of the deposit. The great difficulty is to prevent the deposit at the cathode of other elements than copper. Hence, as a rule, high current-efficiency is a condition (though, perhaps, not the only condition) for a good deposit.

High current-densities (up to 300 amperes per sq. ft.) have been employed in more recent years in connection with processes for making copper tubes and sheets by the electrolytic deposition of copper on rotating cylindrical cathodes.

In electrolytic copper refining, high current-density, though still possible, in theory, is excluded, in practise, for the good reason that "it would not pay." Aside from the increased amount and cost of electrical energy that would result from the use of higher current-densities, there are other important considerations which argue strongly in favor of low current-densities. The electrolyte is more complex and much more variable in chemical constitution by reason of the impurities contained in the anodes, and which eventually pass into the solution, or else form a part of the "slime." This slime contains the precious metals, gold and sliver, which are recovered through the process of refining. It is necessary to guard carefully against loss of precious metals by their being carried over to and deposited on the cathode, either electrolytically or mechanically. This means, practically, that the electrolyte must not be stirred violently; indeed, it can scarcely be stirred at all, to increase diffusion. The difficulties and the cost of maintaining the electrolyte at a high constant conductivity, either by raising the temperature, or by chemical treatment, and the difficulties incidental to circulation or agitation of the solution, are very much greater than in the case of an electrolyte serving for electro-deposition when using anodes of pure copper. Experience has shown that the advantages, such as increased output from a plant of given size, etc., do not offset the disadvantages and the increased cost.

There is also some misunderstanding in regard to the cost of the power required for depositing copper. Paradoxical as the statement may seem, it is possible, theoretically, to deposit any amount of copper with a given amount of electric power. A mathematical demonstration of this possibility was given by me some twenty-five years ago in a series of articles published in the *Electrical Engineer*. The electrochemical principles on which this interesting possibility depend were set forth by Dr. N. S. Keith, the founder and first secretary of this Institute, in the discussion of a paper on "Depositing Vats in Series," read by Mr. Slater, at the first meeting of the A. I. E. E. at Philadelphia, in October, 1884 (see Volume I of the A. I. E. E. TRANSACTIONS). When there is no polarization-effect produced at the anode or the cathode, in other words, when the thermochemical reaction (heat of formation) incidental to the dissolving of copper at the anode is exactly equal to that incidental to the deposit of copper at the cathode, as is the case when electrolysis takes place with a low current-density between plates of pure copper in an electrolyte of pure copper sulphate, all the "ions" then consisting of copper only, there is no consumption of energy except in overcoming resistance. In such a case it is possible to increase the total amount of copper deposited without increasing the total amount of electrical energy expended. Suppose that, in a given case, starting with a certain number of vats in series, we add a second series, exactly like the first one, in multiple. If the current-density in each series be made one-half what it was in the first series, the total current passing through the two series in multiple will be the same as before, and the total amount of copper deposited, on the assumption of 100 per cent current efficiency, would be the same as before. The difference of potential between the anodes and cathodes in each vat will be reduced to one-half, because it only depends on resistance-drop, in the absence of polarization. If we still wish to retain the same working power in the circuit, we may add as many cells again in series to each of the series. We will then have four times the number of vats and four times the number of cathodes on which copper is being deposited with one-half the current density, and, consequently, one-half the rate of deposit that was obtained when one set of vats alone was in use. With four times the number of plates receiving a deposit at one-half the original rate, the total output in copper will be doubled. By increasing the number of series connected in multiple to four, the number of vats in each series could also be increased to four times the original number. The current density for the same total current and energy would be one-quarter what it was originally, but with sixteen times the number of vats and plates in use, the total amount of copper deposited with the same electric power, would be four times what it was before. It is seen that the number of vats, and, consequently, the size and cost of plant necessary to treat such a large amount of copper, would

increase in geometrical ratio as compared with the increase in output, and it is obvious that such a plan would not be economical. The saving in cost of power which might be effected by reducing the current-density to a very low value in a plant arranged as just mentioned, would come far short of offsetting the additional fixed charges and operating expenses of the greatly enlarged plant necessary, to say nothing of the loss of interest resulting from the greatly increased total amount of copper that would be under treatment at the refinery. Refining copper, being a commercial proposition as well as an electrochemical and mechanical problem, must be carried on under conditions which are compatible with the highest economy and which give the most profit. It is found in practise that the best results are obtained when the current-density ranges between 15 and 50 amperes. The exact current-density corresponding to the best financial result will naturally vary somewhat with the locality, design, and operating conditions of the particular refinery.

Lawrence Addicks: The higher the current density the more rapid must be the circulation in order to keep sufficient copper close to the cathode, which is the secret of good deposits. We are limited in that by the silver and gold losses, as the contents of the anode are left as insoluble slime in the tank, and we cannot afford to stir that up and foul the cathode. That is the commercial point which limits us.

I think a 1500-kw. turbine will use 17 lb. of steam per kw-hr. on the same basis on which I have shown the curves of the reciprocating engine. Take the triple-expansion engine at 15 lb., and we have a difference of 2 lb. of steam per kw-hr., which, at 15 cents per 1000 lb. is $39.42 a year, which is $2.60 per kw. Without disputing 18 per cent, that Mr. Longwell wants for depreciation, interest, etc., that allows us to spend $15 per kw. more on that installation, and right on this question of steam consumption, the reciprocating engine for that size unit certainly holds its own.

Mr. Newbury, on the other hand, says that simplicity is a great point, that the reciprocating engine is a complicated affair, and that we would much better have a steam turbine for the prime mover, an alternating-current generator, a transformer, a synchronous converter, and a booster. I think on that score also the reciprocating engine has something to be said for it.

C. H. Vom Baur: The oil engine has been used only to a slight extent in this country in electrochemical industries. Now that oil can be sold in the harbor of New York for less than three cents a gallon, 2.83 cents, actually in lots of 80,000 gallons, and in view of the high load factor in this work, the subject of the oil engine has again come to our attention. These engines will make power for 0.45 of a cent per kw-hr., taking interest and depreciation at ten per cent, and figuring in all the taxes and insurance, including liability insurance. There is so much of this heavy oil on the market, that contracts are made for a number of years.

These oil engines have been made in Europe in sizes as large as 2000 h.p. to a cylinder, so with the average size plant in which engines are used in this electrochemical industry, and with the average size unit, all the conditions can easily be met with the oil engine and with the oil that is now on the market.

Lawrence Addicks: There seems to be no question that it is possible to do better with the gas engine than the best that could be done in the case of steam. I looked at one of the oil engine installations in this country recently, I think it was of 400 or 500 h.p. capacity. The only difficulty with it was that it was subject to heart failure, and when it had one of these strokes and was shut down, there was considerable difficulty in getting it started. I think this engine is about two years old, and it has not shown the reliability that we feel is necessary in electrolytic work.

H. E. Longwell: As I understand it, the object of the meeting tonight is to consider what is, and what is not, a suitable prime mover for electrolytic plants; and when I say I do not think the gas engine is most desirable for the specified operating conditions, I do not want any one to get the idea that I do not think the gas engine has its uses. Neither do I want you to get the idea that I do not think the low-pressure steam turbine has its legitimate field of usefulness.

I have discussed the several types of power plant solely with reference to the operating conditions as I understand them, and I have endeavored to do it impartially and dispassionately. I also wish to assure you that my advocacy of the complete expansion turbine for this service, is entirely disinterested, and is based only on what in my estimation are sound principles of commercial engineering.

F. D. Newbury: Some criticism has been aimed at what I, in writing the paper, considered the least important part of the paper—the waterwheel-driven plant. The steam-driven plant is, of course, the one in which the copper refiners in the vicinity of New York are mainly interested.

In connection with the criticism of the size of waterwheel plant considered, it was not brought out in the paper as probably it should have been, that waterwheel plants are used mainly in the aluminum industry where large amounts of power are required, and for that reason a large plant was purposely selected. Experience has shown that in such plants the apparently more complicated power plant consisting of two or three links is in reality simpler, more reliable, more efficient, and less costly to maintain, than the installations consisting simply of the waterwheel and generator. With plants of 1000 kw. or 1500 kw. or even 2000 kw., I agree that the alternating-current generator and synchronous converter cannot compete with the direct-connected generator, if the plant can be located near the place of utilization of the current. In such circumstances, the distance of transmission is the only thing that would dictate the use of the alternating current-direct current system.

The possible difference between calculated and actual efficiencies was mentioned. The efficiencies of the various classes of apparatus given in this paper represent actual operating efficiencies, liberal allowance having been made for all losses.

Several of the speakers questioned my consistency in emphasizing the necessity of simplicity and, at the same time, advocating a plant involving the alternating-current generator, synchronous converter, and in some cases transformers and the synchronous booster. This position is entirely consistent and I believe Mr. J. B. Herreshoff will bear me out when I say that with the long experience he has had with most of the types of apparatus discussed, the one piece of apparatus he has had the least trouble with has been the synchronous converter. Obviously an alternating-current generator is more reliable, more efficient, than even a low-speed direct-current generator.

Mr. Herreshoff spoke of the possibility of obtaining to a certain extent voltage regulation with two synchronous converters supplied from one alternating-current generator, by variation in power factor. What he said is perfectly true, but if that method is contemplated, it must be taken into consideration by the machine designer and properly allowed for, because a slight difference in power factor will mean a very considerable increase in local heating, and unless the converter is designed for that condition, it may cause a burn-out near the tap coil.

F. W. Harris (by letter): One very real advantage of the a-c. generator-sychronous converter plant over the d-c. generator plant lies in the fact that interchange of power with other stations is then possible. There is now little or no market for 250-volt d-c. current even in the cities and in the neighborhood of electrolytic plants there is none. The sale of excess d-c. power is therefore not practicable. On the other hand, there is a ready market for excess a-c. current at any standard frequency, and in an emergency, additional power can often be bought. There are certain seasons when power commands a premium and the fact that the power produced is a marketable commodity is an important one.

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PROTECTIVE REACTANCE IN LARGE POWER STATIONS

BY JAMES LYMAN, ALLEN M. ROSSMAN AND LESLIE L. PERRY

ABSTRACT OF PAPER

The concentration of a large generating capacity on the busbars of a single power station demands protection against an excessive flow of current into an accidental fault. Reactance coils can be used in various ways to limit the instantaneous current flow. Reactance coils in the generator leads, while limiting the flow of current from the different generators, are not efficient for limiting the current flow into a fault.

Bus reactances are less bulky and less expensive than generator reactances; are more efficient in controlling the current flow, and have the advantage of localizing the effect of a fault to one or more sections of the busbars. They have the disadvantage that, under normal conditions of operation, the current flow across them may cause an undesirable drop in voltage.

The ideal system of bus reactances would afford maximum protection to service and equipment in emergencies but, under normal operating conditions, would give minimum voltage difference between various points in the busbars. The straight bus, the ring bus, and the ring and transfer bus approach this ideal condition in the order named.

Reactance coils in each feeder circuit are extremely effective in limiting the flow of current into a short circuit on the feeder and in isolating the effects of this short circuit from the other parts of the system.

THE PRESENT tendency in power generation is toward larger central stations and larger units and consequent concentration of large amounts of power on one set of busbars. The reasons for this tendency are, the smaller total capital investment required, the lower operating expenses, and the higher operating efficiencies obtained.

That the concentration of a large amount of generating capacity on one set of busbars can give rise to very destructive effects, in cases of accidental short circuits on busbars or on feeders, has been proved by the experience at some time or other of many of the larger central stations. A short circuit or a ground on a feeder, the failure of a current transformer, the hanging of an arc at a fuse, or the throwing on the busbars of a generator slightly out of phase, have resulted in tearing out generator and transformer windings, blowing oil switches to pieces, and even in the destruction of masonry walls. In milder

cases these effects are shown by distortion of end windings on generators and transformers and by oil throwing, or tank distortion, of oil switches.

To limit the flow of energy into faults, reactance coils have been employed in various ways. It is the purpose of this paper to show some of the ways in which these reactances may be employed and the limits of economical application in each of the systems discussed.

Various Arrangements of Reactance Coils

The reactance which is inherent in the design of all a-c. generators may be augmented by additional reactance coils located as follows:

a. In the generator leads.
b. In tie lines between different power stations.
c. Between different sections of the station busbars.
d. In the station busbars between adjacent generator connections.
e. Combinations of any of the above systems.
f. In feeder circuits.

Generator Reactance—Inherent or External

Reactance inherent in the design, or reactance coils in the external leads, of generators, afford protection to the armature windings by limiting the amount of current that can flow through these windings, in the case of a short circuit on the busbars or feeders. The amount of instantaneous current flow varies, approximately, inversely as the total amount of the reactance.

The amount of current which can flow into a short circuit is limited by the amount which can flow from the generators. These reactances are therefore useful in limiting the total amount of current flow into a short circuit and the resultant destructive effects at this point.

There are two objections to the use of large reactance coils in the generator leads for limiting the total kv-a. which can flow into a short circuit on a very large system. The first of these is that, from the nature of their location, they must be designed to carry the entire current output of the generators and hence their kv-a. ratings are high and they become expensive and bulky.

The second objection is, that a short circuit on any section of the busbars will cause a drop in voltage at all points on the

busbars of approximately the same degree, and the service on *all* feeders distributing from this station will suffer in consequence.

It therefore appears that the most important function of reactance coils in the generator leads is to protect the generator windings.

Sectionalizing Reactances

Reactance coils may be placed in tie lines between stations, in the busbars between different sections of the same station, or even in the busbars between adjacent generating units connected to the busbars. The function of these sectionalizing reactances is to permit the parallel operation of, and the free exchange of current between, different parts of the system, and at the same time limit the amount of current which would otherwise flow from all sections into a short circuit on any one section. If reactance coils are suitably selected, it is possible so to confine a fault to the section in which it originates, that adjacent sections are not seriously affected and hence service is impaired only on that section in which the fault originates.

Reactance coils for this service are, as a rule, not designed to carry the full current generated, and are therefore less expensive and less bulky than those placed in the generator leads.

Where considerable power must be transmitted over these reactance coils, the amount of reactance that can be employed is limited by the permissible voltage drop across them. For instance, in a large station, during periods of light load, it will be desirable to carry the entire load on one or two generators and distribute from feeders all along the bus. If the running generators are at one end of the busbars and if the power distributed from the other end of the busbars must pass over several sectionalizing reactance coils, there may be, in the case of large reactances and low power factor, a considerable voltage drop across these reactances and a resulting difference in voltage between the two ends of the busbars.

It is obvious from the above that the best results will be obtained from a judicious combination of generator reactances to protect the machines, and sectionalizing reactances to protect the service.

Busbar Systems

In laying out the busbar system for a large new power station the designing engineer should therefore consider, in addition to safety, simplicity, and flexibility, the adaptability of the system

to the installation of sectionalizing reactance coils. Some of the more common systems of arranging busbars are shown diagrammatically in Fig. 1. These are:

a. Single straight bus.
b. Double straight bus.
c. Single ring bus.
d. Double ring bus.
e. Single straight bus and direct feed.
f. Single ring and single straight bus.

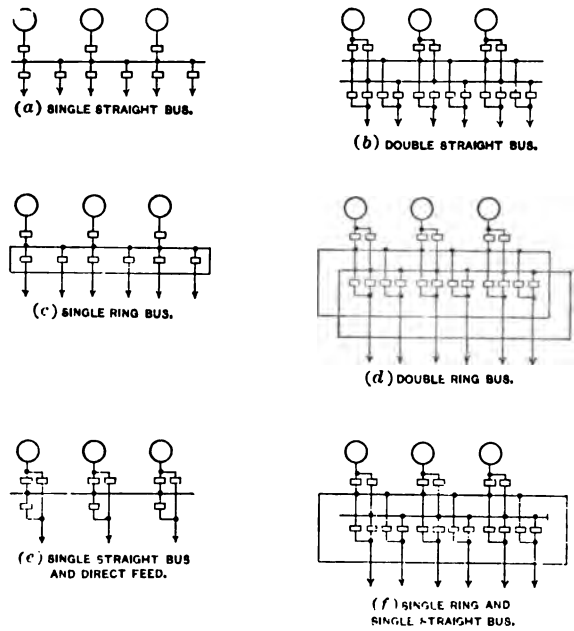


FIG. 1—SINGLE-LINE DIAGRAMS OF TYPICAL SYSTEMS OF CONNECTION

ANALYSIS OF APPLICATIONS OF REACTANCE COILS

For analyzing the effects of reactance coils as outlined above a power station of nine (9) generators has been assumed. It is further assumed that these generators are of the same size and design and that each one has 10 per cent inherent reactance. Based on these assumptions, a series of curves has been plotted to show the effect of variations in the size and location of the reactance coils.

In a large station, when all of the generating units are not in

operation, it is usually desirable from the boiler room and coal handling point of view, to operate adjacent machines, and, with a few exceptions that are specially noted, the curves are based on such operation. It is further assumed that the power is evenly distributed from the different sections of the busbars.

Where kv-a. values are given they are based on an assumed rating of 25,000 kv-a. for each generator; the curves and all other values are general, as far as kv-a. rating is concerned, and can be applied to generators of any rating. All reactance ratings, except feeder reactances, are given in the percentage reactive voltage drop that would occur if the rated current of one generator were passed through them.

For the sake of brevity, the computations used in deriving the curves have been omitted. The methods of derivation are, however, exceedingly simple and for the benefit of those who wish to verify the curves, typical computations are given in an appendix.

Reactance in Generator Leads

Fig. 2 shows the relation between per cent reactance in generator leads and short-circuit current on the busbars, for different assumed values of reactances, with 1 to 9 generators connected to the busbars.

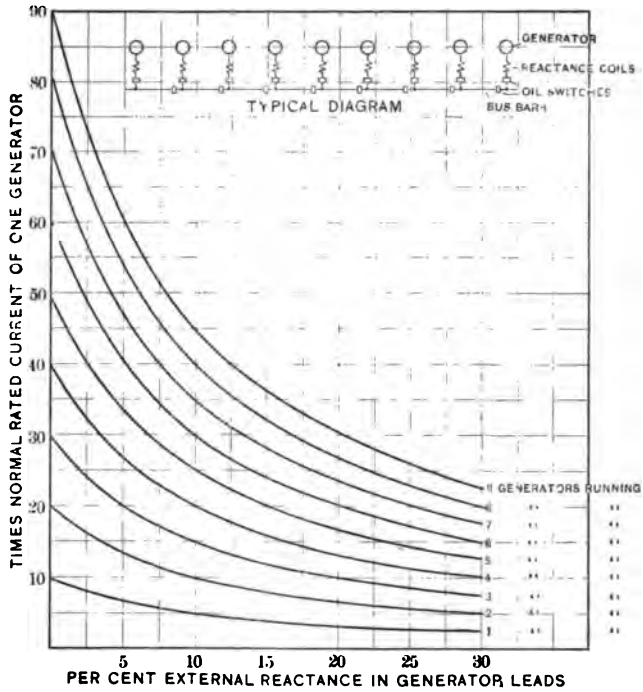
These curves show that the first few per cent of reactance added are much more effective in reducing the short-circuit current than are subsequent additions. Starting with the inherent reactance, only, of the generators, the addition of 5 per cent external reactance reduces the short-circuit current by $33\frac{1}{3}$ per cent; the second 5 per cent reactance reduces it by $16\frac{2}{3}$ per cent; the third 5 per cent reactance reduces it by 10 per cent; the fourth 5 per cent reactance by $6\frac{2}{3}$ per cent, etc., until the effect of further additions becomes infinitesimal.

With nine 25,000-kv-a. generators in operation it will be noted that each generator requires 20 per cent reactance in its leads, a total of 45,000 kv-a., to limit the current flow to 30 times the rated current of one generator, or to 750,000 kv-a., based on actual current flow and normal voltage of the system. The value 750,000 kv-a. has been selected as a limiting value because it approaches the maximum rupturing capacity specified by one or two of the large manufacturers for the heaviest duty oil switches now on the market.

REACTANCE IN BUSBARS—SINGLE OR DOUBLE STRAIGHT BUS

Figs. 3, 4, and 5, show the relation between per cent reactance in busbars and short-circuit current on the busbars, assuming nine generators running. Each figure shows four curves:

Curves (*a*) and (*b*) assume a fault developing in the center of the busbars, while (*c*) and (*d*) assume a fault at the end of busbars.



Relation between per cent external reactance in generator leads and maximum current flow into a short circuit on the busbars.
Inherent reactance of each generator = 10 per cent.
Reactance in busbars = 0.

FIG. 2

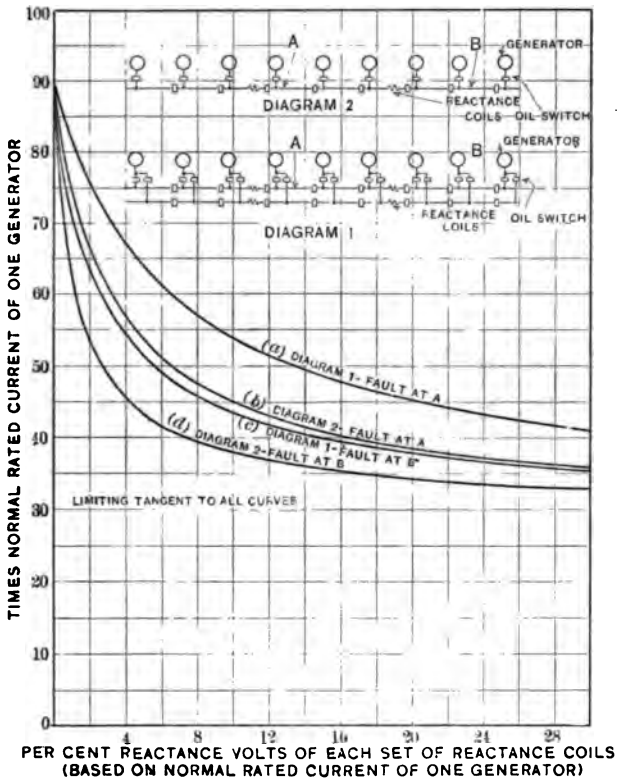
Curves (*b*) and (*d*) apply to a single straight bus, while curves (*a*) and (*c*) apply to a double straight bus.

Fig. 3 covers reactance in busbars between groups of three generators per group.

Fig. 4 covers reactance in busbars between groups of two generators per group, and in this case the number of generators has been increased to ten to obtain a symmetrical arrangement.

Fig. 5 covers reactance in busbars between the individual generators.

With double busbars there are required twice as many reactance units as with single busbars, but inasmuch as with the double bus each reactance carries but one-half the current carried by each reactance in the single bus, the total kv-a. required will be the same in either case.

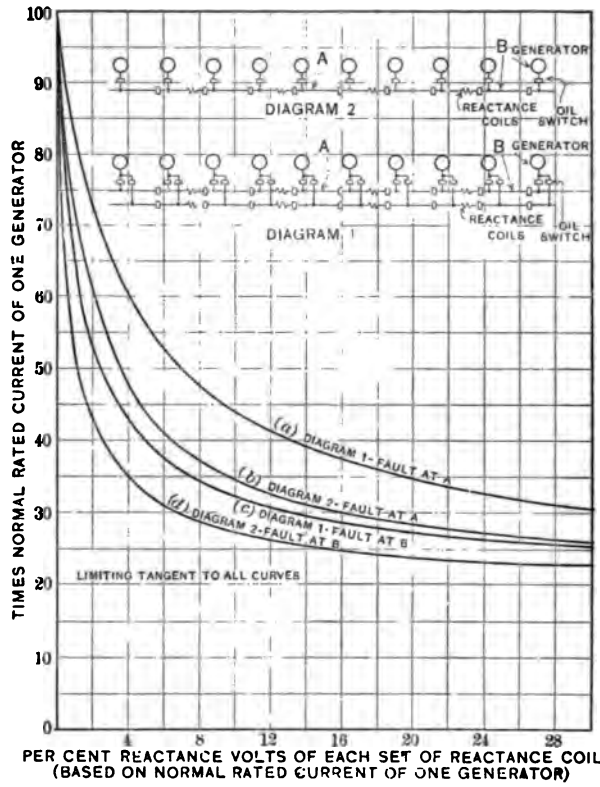


Relation between per cent reactance in busbars and maximum current flow into a short circuit on the busbars.
Type of Bus: Straight, single and double.
Reactance coils located between groups of three generators per group.
Inherent reactance of each generator = 10 per cent.
External reactance in each set of generator leads = 0.
Number of generators running = 9.

FIG. 3

Comparing similar curves in Figs. 3 and 5, it will be seen that a given total per cent in reactance has a greater choking effect when distributed between adjacent generators than when more concentrated by placing between groups of three generators per group, and that this difference increases as the amount of reactance is increased. For example:

Comparing the (*b*) curves, 16 per cent total reactance divided into two units of 8 per cent each will prevent the current from exceeding 48 times normal rated current of one generator, while this same reactance divided into eight units of 2 per cent each will limit the current to 44.5 times. Likewise 32 per cent re-



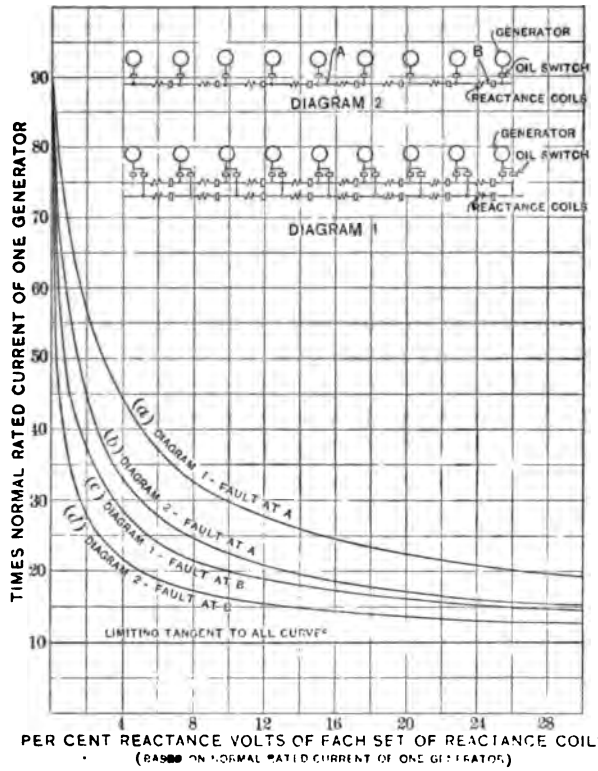
Relation between per cent reactance in busbars and maximum current flow into a short circuit on the busbars.
Type of Bus: Straight, single and double.
Reactance coils located between groups of two generators per group.
Inherent reactance of each generator = 10 per cent.
External reactance in each set of generator leads = 0.
Number of generators running = 10.

FIG. 4

actance in two units of 16 per cent each, limits the current to 40.5 times, while in eight units of 4 per cent each it will limit the current to 33 times. 60 per cent reactance in two units of 30 per cent each limits the current to 36 times, while in eight units of 7½ per cent each it will limit the current to 25.5 times.

Considering again the case of the nine 25,000-kv-a. genera-

tors in which the short-circuit current is limited to 30 times the normal rated current of one generator, and assuming all reactance coils to have one-half the current carrying capacity of the generators, and remembering that the kv-a. reactance rating varies as the square of the current, it will be seen that under the worst condition of short circuit ((*a*) curves) with reactances between



Relation between per cent reactance in busbars and maximum current flow into a short circuit on the busbars.
Type of Bus: Straight, single and double.
Reactance coils located between *adjacent* generator connections.
Inherent reactance of each generator = 10 per cent.
Exteral reactance in each set of generator leads = 0.
Number of generators running = 9.

FIG. 5

groups of three generators, infinite reactance would be required; with reactances between groups of two generators the reactance required is $0.32 \times 8 \times \frac{25,000}{4} = 16,000$ kv-a.; with reactances between adjacent generators the reactance required is $0.10 \times 16 \times \frac{25,000}{4} = 10,000$ kv-a.

There is another advantage to be gained by placing reactances between adjacent generators, namely; in case of a short circuit the full effect of the so-called " hammer blow " is felt by but one generator—the one on the same section with the short circuit—while all other generators are more or less isolated from this trouble by one or more sets of reactance coils.

Reactance in Busbars—Single or Double Ring Bus

By tying together the ends of the busbars shown in diagram Fig. 5, and inserting reactance coils at the point of joining, we obtain a ring bus and gain the advantages that we would get by always operating the middle group of generators on a straight bus. Three important advantages gained, are:

1. Because of the two paths to any section of the busbars, the current carrying capacity of the reactances can be halved and consequently the kv-a. rating can be quartered.
2. A given current in traveling between the two most remote points on the busbars passes over one-half the number of reactances that it would encounter in traveling from end to end of the straight bus, and therefore the voltage drop is cut in half.
3. It is possible to cut out any section of the busbars without in any way interfering with the parallel operation of the remaining portion of the busbars.

It is obvious from an examination of the connection diagrams in Fig. 3, 4, and 5, that the short-circuit currents for *any* point on the single or double ring bus are shown by curves (*a*) and (*b*) on these sheets.

Voltage Difference along Busbars

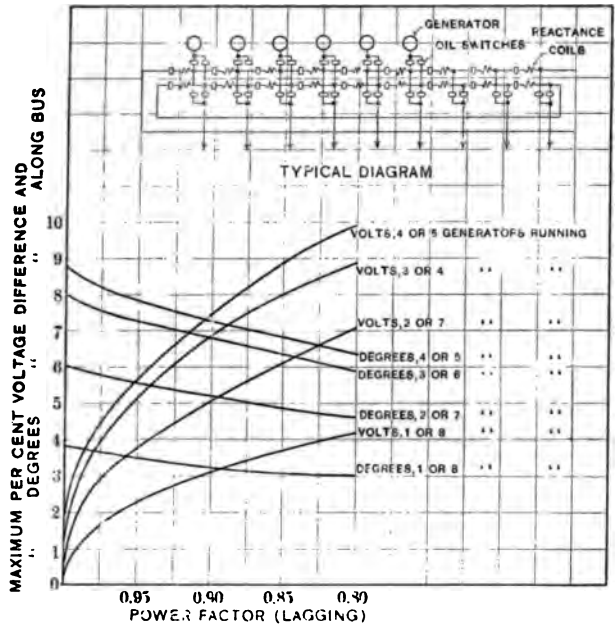
It was previously stated that with heavy sectionalizing reactance coils in the busbars it is possible, under certain conditions of operation, to get an objectionable difference in voltage along the busbars.

Fig. 6 is plotted to show the maximum voltage difference and the maximum angular difference of voltage that will exist along the busbars with a double ring bus and 12 per cent reactance between adjacent generator sections in each bus, with one to nine generators running at a power factor between 1.0 and 0.8 lagging, and an even distribution of load along the busbars. It will be noted that a maximum voltage difference of 9.9 per cent can exist with four or five machines running at 0.8 power

factor, and a maximum angular difference of 8.75 degrees can exist with the same number of machines running at unity power factor.

Crossed Generator Leads

Fig. 7 differs from Fig. 6 in that adjacent generator leads do not go to adjacent sections of the busbars but are cross-connected



Relation between maximum voltage difference and maximum angle of displacement between voltages along bus as ordinates and power factor as abscissas, assuming adjacent generators running and an even distribution of load on the different bus sections.
Adjacent generators connected to *adjacent* sections of the busbars.
Type of Bus: Double ring.
Reactance coils located between adjacent generator connections in both buses.
Rating of each set of reactance coils = 12 per cent (based on normal rated current of one generator)
Inherent reactance of each generator = 10 per cent.
External reactance, in each set of generator leads = 0.
Number of generators running = 1 to 9.

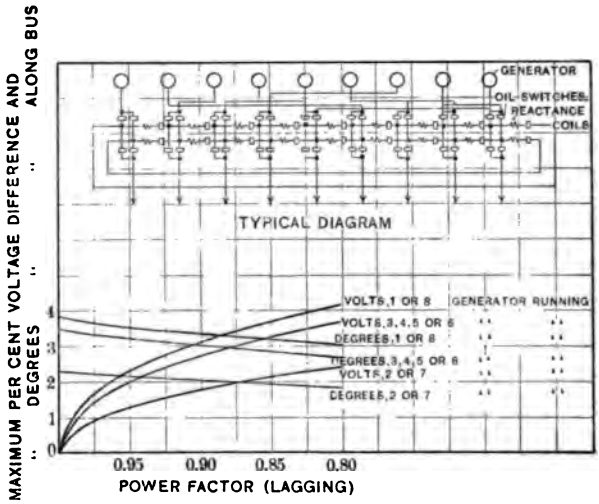
Fig. 6

in such a manner as to give minimum voltage difference along the busbars when operating adjacent generators. The order of connecting to the busbars is shown by the diagram of connections in Fig. 7. It will be noticed that with this arrangement of leads the maximum voltage difference along the bus is materially reduced; the maximum point on Fig. 7 being 4.2 per cent as against 9.9 per cent on Fig. 6. An inspection of the diagram

also shows that the short-circuit curves shown by (*a*) and (*b*) on Fig. 5 also hold for this case of cross-connected generator leads.

This arrangement of generator leads has certain disadvantages, the chief of which is that some of the leads of the older generators have to be changed to different locations on the busbars as the station is extended and new units are added.

Also, it is undesirable to have long longitudinal runs and sev-



Relation between maximum per cent voltage difference and maximum angle of displacement between voltages along bus as ordinates and power factor as abscissas, assuming adjacent generators running at normal rated current and an even distribution of load from the different bus sections.

Alternate generators connected to *adjacent* sections of the busbars.

Type of Bus: Double ring.

Reactance coils located between adjacent generator connections in both buses.

Rating of each set of reactance coils = 12 per cent (based on normal rated current of one generator)

Inherent reactance of each generator = 10 per cent.

External reactance in each set of generator leads = 0.

Number of generators running = 1 to 9.

FIG. 7

eral crossings of generator leads; these runs should be as short and direct as possible.

PROTECTION VERSUS REGULATION

The curves have shown that with reactance coils permanently connected in the busbars, the larger the reactance the better the protection against short circuits. On the other hand, the larger the reactance the worse the voltage regulation along the busbars. It is therefore evident that it would be desirable to adopt some method of shunting the reactance coils when they

are not needed for protection. The most direct way of accomplishing this would be to short-circuit the reactances. This introduces an oil switch for each set of reactance coils.

Ring and Transfer Bus

A simple method of shunting reactance coils when they are not needed is by the use of a ring and transfer bus. The connections of this system for one to nine adjacent generators running, together with the direction and amount of the current flow in each path, on the assumption that the load is evenly distributed along the bus, are shown in Fig. 8.

The main bus is a ring bus provided with reactances between adjacent generator sections, while the transfer bus may be either a straight or a ring bus and is without reactances.

With this system of connections, the middle one of the running generators is connected to both main and transfer buses, while all other running generators are connected to the main bus only. A simple system of interlocks can be provided between generator oil switches to prevent more than one generator at a time from being connected to the transfer bus. On every bus section the oil switches connecting the generators to the main bus should be interlocked with the oil switches connecting the feeders to the transfer bus so that it will not be possible for the operator to shunt the reactances when they should be in service.

Fig. 9 is plotted to show the maximum short-circuit currents obtainable on the busbars with the ring and transfer bus operated as outlined above, with 12 per cent, 8 per cent and 6 per cent reactances respectively between adjacent generator sections in the ring bus, with one to nine adjacent generators running.

From Fig. 9 it will be seen that the maximum short-circuit current occurs with eight machines in service. With 12 per cent bus reactances this current may reach 30.8 times the normal rated current of one generator. These curves show that the short-circuit current is less with nine machines running than with four, five, six, seven, or eight machines running. The reason for this is, that in the latter cases there are two parallel paths between some portions of the system, while with nine generators there is but one path.

Fig. 10 is plotted to show the maximum voltage difference that will exist along the busbars with the ring and transfer bus operated as outlined above, with 12 per cent, 8 per cent and 6 per cent reactances, respectively, between adjacent generator

sections in the ring bus, assuming one to nine adjacent generators operating at 1.0 to 0.8 lagging power factor and an even distribution of load along the busbars.

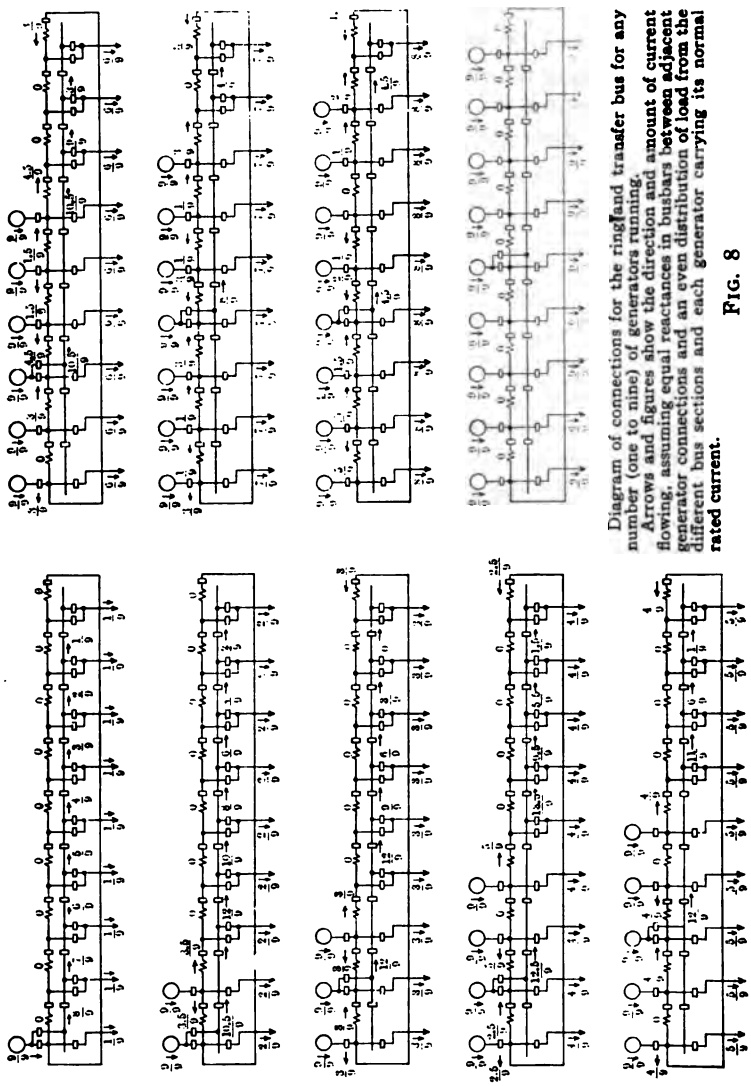


Diagram of connections for the ring and transfer bus for any number (one to nine) of generators running.
Arrows and figures show the direction and amount of current flowing, assuming equal reactances in busbars between adjacent generator connections and an even distribution of load from the different bus sections and each generator carrying its normal rated current.

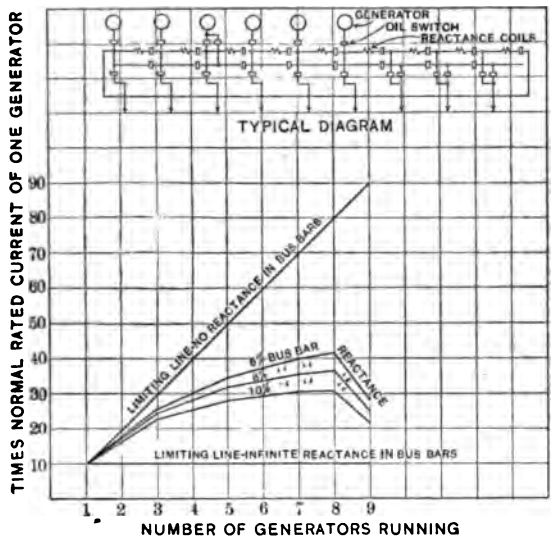
FIG. 8

From Fig. 10 it will be seen that the maximum voltage drop occurs with six generators running, but that this is considerably less with a larger or a smaller number of generators in service.

With 12 per cent bus reactances, the maximum voltage difference along the busbars under the conditions specified is 5 per cent.

If other than adjacent generators are operated it is possible with a given bus reactance to obtain higher values of short-circuit currents than are shown in Fig. 9 and lower maximum voltage drops than are shown in Fig. 10.

Fig. 11 is plotted to show the values of short-circuit current



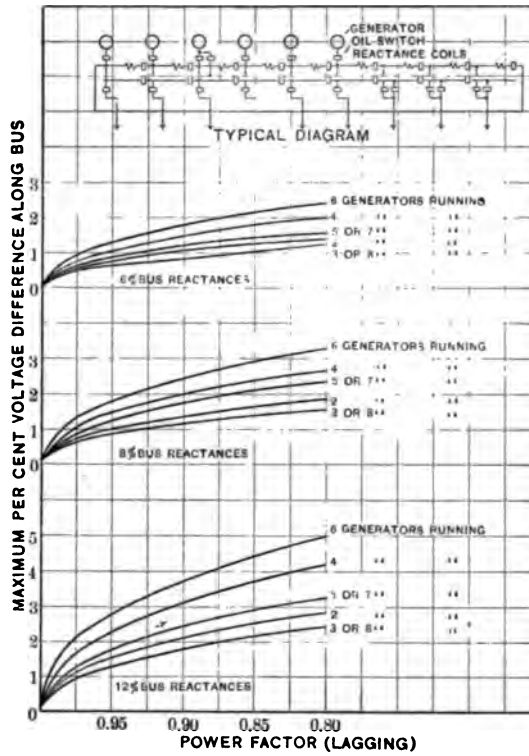
Relation between maximum current flow into a short circuit on the busbars and number of adjacent generators running.
Type of Bus: Ring and transfer.
Reactance coils located between adjacent generator connections in the ring bus only.
Ratings of each set of reactance coils, 6, 8 and 12 per cent, respectively (based on normal rated current of one generator)
Inherent reactance of each generator = 10 per cent.
External reactance in each set of generator leads = 0.
Number of generators running = 1 to 9.
Method of Operating: The middle one of the running generators to be connected to both main and transfer bus; all other generators are to be connected to main bus only. On each section the oil switch between generator and main bus to be interlocked with the feeder switches between feeders and transfer bus, so that they cannot both be closed at the same time; feeder switches closed on both buses when generator on same section is not connected to bus.

FIG. 9

that would be obtained if the generators were so selected as to give the maximum possible values, with bus reactances chosen at 6, 8, 12, 20, and 30 per cent, respectively. With 12 per cent reactance it will be noted that the short-circuit current may reach nearly 38 times the normal rated current of one generator. The reason for the higher values of short-circuit current in this case is that there are several parallel circuits between the ring

and the transfer bus, so arranged as to give the path of least reactance between these buses.

Obviously this method of operation is abnormal and the curves of voltage drop are therefore not of special interest.



Relation between maximum per cent voltage difference along bus and power factor, assuming adjacent generators running at normal rated current and an even distribution of load from the different bus sections.
Type of Bus: Ring and transfer.
Reactance coils located between adjacent generator connections in the ring bus only.
Ratings of each set of reactance coils 6, 8 and 12 per cent respectively, (based on normal rated current of one generator)
Inherent reactance of each generator = 10 per cent.
External reactance in each set of generator leads = 0.
Number of generators running = 1 to 9.
***Method of Operating*: The middle one of the running generators to be connected to both main and transfer bus; all other generators are to be connected to main bus only. On each section the oil switch between generator and main bus to be interlocked with the feeder switches between feeders and transfer bus, so that they cannot both be closed at the same time; feeder switches closed on both buses when generator on same section is not connected to bus.**

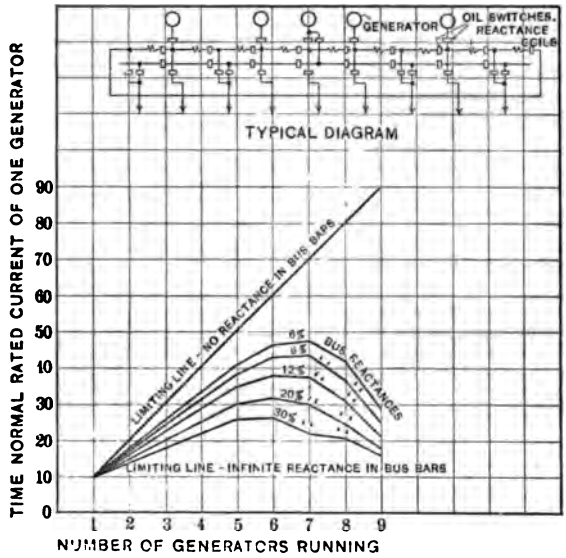
FIG. 10

CURRENT-CARRYING CAPACITY OF REACTANCES

It was stated above that reactance coils in generator leads must be designed to carry the normal rated generator current. It was shown that in the ring bus the bus reactances might be

of one-half the current-carrying capacity of the reactances used on the straight bus.

Fig. 8 shows that with any number of adjacent generators in operation at their normal rated loads and the station load evenly distributed from the different sections of the busbars, the maximum current flow across any bus reactance coil is 5/9 the normal rated current of one generator.



Relation between maximum current flow into a short circuit on the busbars and number of generators running, generators being selected to give the greatest possible short-circuit current.

Type of bus: Ring and transfer.

Reactance coils located between adjacent generator connections in the ring bus only.

Ratings of each set of reactance coils, 6, 8, 12, 20 and 30 per cent respectively (based on normal rated current of one generator)

Inherent reactance of each generator = 10 per cent.

External reactance in each set of generator leads = 0.

Number of generators running = 1 to 9.

Method of Operating: The middle one of the running generators to be connected to both main and transfer bus; all other generators are to be connected to main bus only. On each section the oil switch between generator and main bus to be interlocked with the feeder switches between feeders and transfer bus, so that they cannot both be closed at the same time; feeder switches closed on both buses when generator on same section is not connected to bus.

FIG. 11

The proper current-carrying capacity for any other system may be found by constructing diagrams similar to those of Fig.8.

COMPARISON OF SYSTEMS—TABULATION

The accompanying tabulation shows the number, size, and effect on voltage regulation of reactances used on each of the systems discussed in this paper, based on a limiting short-cir-

System of Arranging Reactances	Max. short circuit current possible on busbars; based on normal rated current of one generator = 1.	Number of sets of three-phase reactance units required.	Per cent reactance volts of each set of coils, based on normal rated current of one generator.	Current carrying capacity of each reactance; based on normal rated current of one generator = 1.	Total per cent kv-a. rating of reactance, based on rating of one generator = 100 per cent.	Total kv-a. reactance, assuming nine 25,000 kv-a. generators.	Max. percentage voltage difference along busbars.
Reactances in Generator Leads	30	9	20	1	180	45,000	0
Reactances in Busbars—Straight bus							
Between groups of 3 generators per group (Single bus)	30	2	∞	2	∞	∞	Not computed
Between groups of 3 generators per group (Double bus)	30	4	∞	1	∞	∞	
Between groups of 2 generators per group (Single bus) } 10 Generators	30	4	16	2.4	368	92,000	
Between groups of 2 generators per group (Double bus) } 10 Generators	30	8	32	1.2	368	92,000	
Between adjacent generators (Single bus)	30	8	5	2.22	197	49,250	
Between adjacent generators (Double bus)	30	16	10	1.11	197	49,250	
Reactances in Busbars, between adjacent generators—Ring bus.							
Generator connections direct (Single bus)	30	9	5	1.11	55.5	13,888	9.9
Generator connections direct (Double bus)	30	18	10	0.555	55.5	13,888	9.9
Generator connections crossed (Single bus)	30	9	5	0.666	20	5,000	4.2
Generator connections crossed (Double bus)	30	18	10	0.333	20	5,000	4.2
Ring and transfer bus, reactances in ring bus only, generator connections direct	30.8	9	12	0.555	33.3	8,333	5

cuit current of approximately thirty times the normal rated current of one generator.

The ring bus with crossed generator leads as per diagram Fig. 7, requires the least reactance and gives the lowest voltage drop along the busbars.

The ring and transfer bus requires 60 per cent of the reactance required by the ring bus with direct generator connections, and 18½ per cent of that required for inserting in the generator leads.

Under normal conditions of operation at 0.8 lagging power factor with any number of adjacent generators running, and load evenly distributed from the different bus sections, there is no difference of potential along the busbars when the reactances are in the generator leads only; 4.2 per cent maximum difference when the ring bus is used and the generator leads are crossed; 5 per cent maximum difference when the ring and transfer bus is used and the generator leads are direct.

Ring and Transfer Bus with Crossed Generator Connections

The two systems which have shown the most economical application of reactances to limit the flow of short-circuit current and at the same time have given the lowest voltage drop along the busbars under the conditions stated, have been the ring bus with the generator leads crossed and the ring and transfer bus. It would therefore appear that a combination of these two systems, in which generators 1, 2, 3, 4, 5, 6, etc., are connected to sections 1, 3, 5, 7, 9, 2, etc., would give still better results.

By consulting Fig. 11 it will be seen that with only five generators running, each bus reactance must be designed to give 20 per cent reactive volts. Under the conditions of operation assumed, each reactance should be designed to carry 0.389 times the normal rated current of one generator. This amounts to 27.2 total per cent reactance based on rating of one generator = 100 per cent. This is greater than the 20 per cent shown by the simpler ring bus with crossed generator leads. Moreover, it can be easily shown that the voltage difference along busbars for the assumed conditions is not improved by this connection. This system can therefore be dropped from further consideration.

Feeder Reactances

As grounds and short circuits are more commonly experienced on feeders outside the power station than on the busbars inside

the power station, an additional protection to service and apparatus is afforded by placing reactance coils in the circuit of each feeder connected to the busbars.

As has been previously shown, reactance in the busbars tends to confine the effect of short circuits to the section of bus on which they occur. By placing reactance coils in the feeders we place an additional barrier between the source of trouble on the feeder and the section of busbars to which this feeder is connected. This point will perhaps be best illustrated by considering the case of a short circuit on a feeder just outside the power station and determining the effect of this short circuit on various sections of the busbars both with and without feeder reactances. For this example assume nine 25,000-kv-a. generators in service on the ring and transfer bus system (which with

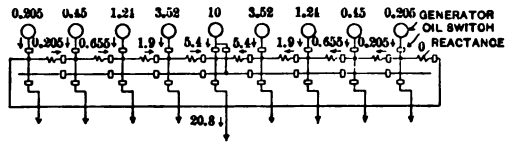


Diagram showing maximum amount and direction of flow of current in all parts of the system where feeder reactances are not used, assuming a short circuit on any feeder.
Type of Bus: Ring and transfer.
Reactance coils located between adjacent generator connections in the ring bus only.
Rating of each set of bus reactance coils = 12 per cent (based on normal rated current of one generator)
Inherent reactance of each generator = 10 per cent.
External reactance in each set of generator leads = 0.
Number of generators running = 9.

FIG. 12

nine generators becomes a pure ring connection), 12 per cent reactance between each generator and a short circuit on any feeder.

Fig. 12 shows the direction of flow and the amount of current in each set of generator leads and on each section of busbars where feeder reactances are not used.

Fig. 13 shows similar results where each feeder is provided with 3 per cent reactance based on a normal rating of 5000 kv-a.

A comparison of Figs. 12 and 13 shows that the addition of the feeder reactance has reduced the short-circuit current into a feeder from 20.8 times to 5.05 times the normal rated current of one generator; *i.e.*, to less than ¼ of its former value. The current flowing from each generator and in every part of the busbars is also reduced to 1/4 of its former value.

It is obvious from Fig. 13 that, with the relatively small amount of current flowing into a feeder short circuit, and the relatively small amount of this current which flows from bus sections adjacent to the fault, the disturbance in voltage on the system will be local only. On the section of the busbars to which the faulty feeder is connected, the drop in voltage will be only about 25 per cent. At 0.8 power factor, 5000 kv-a. flowing over 3 per cent reactance will give a voltage drop of approximately 1.9 per cent.

General Comments

The question naturally arises, what effect will a voltage difference along the busbars have on the service of the system?

On a power system, the feeders of which go direct to light and power distributing transformers, it is desirable that the voltage

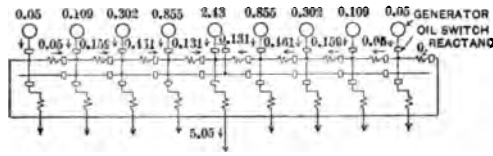


Diagram showing maximum amount and direction of flow of current in all parts of the system where reactance coils are placed in each feeder circuit, assuming a short circuit on any feeder.
Type of Bus: Ring and transfer.
Bus reactance coils located between adjacent generator connections in the ring bus only.
Rating of each set of bus reactance coils = 12 per cent (based on normal rated current of one generator)
Rating of each set of feeder reactance coils = 3 per cent (based on 5000 kv-a. flowing)
Inherent reactance of each generator = 10 per cent.
External reactance in each set of generator leads = 0.
Number of generators running = 9.

Fig. 13

on the busbars be as nearly constant as possible. When the voltage drop between the busbars and the center of distribution is large, it is usually taken care of by placing feeder regulators in the feeder circuit at the power station end and boosting the voltage of the feeder by an amount equal to the drop. This system of distribution is not adapted to handling economically the output of very large power systems and therefore does not call for the extensive application of reactance coils.

On power systems such as exist in most of our largest cities, it is customary to first transmit the power, at voltages ranging from 6600 volts to 22,000 volts, to substations conveniently located, transform to a lower voltage at the substations, and then distribute. Because of the greater distances of transmission, and the double transformation between the power station and the

customers' premises, feeder regulators are practically necessary on the distribution feeders leaving the substations. Any difference in voltage on the busbars will be equalized by these regulators before the power is delivered to the customers' premises.

In this country the feeders between the largest power stations and substations are usually operated as radial feeders, that is, are not tied together at the substation end. This condition of operation is assumed in this paper. If feeders were paralleled at the substations, there would be two tendencies:

1. A tendency to shunt the bus section reactances; and
2. A tendency for a feeder from the section of the busbars having the higher voltage to carry more current than a feeder connected to a section of lower voltage. A discussion of these interesting features, is, however, beyond the scope of this paper.

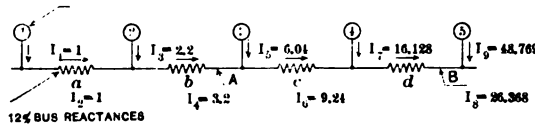
APPENDIX

The points for plotting the curves of Fig. 2 were obtained by the following formula:

$$\frac{100\% \times \text{number of generators}}{\%\ \text{inherent reactance} + \%\ \text{external reactance}} = \text{short-circuit}$$

current expressed in times normal rated current of one generator.

The points for plotting the curves of Figs. 3, 4, 5, 9 and 11 and the values shown on Figs. 12 and 13 were obtained by the following typical method:



Consider first a fault at A.

Assume $I_1 = 1$. This current flows over reactances a without additions or subtractions and therefore

$I_2 = I_1$

$I_3 \times 10 = (I_1 \times 10) + (I_2 \times 12)$, or $I_3 = 2.2$

$I_4 = I_3 + I_2 = 3.2$

$I_5 \times 10 = (I_3 \times 10) + (I_4 \times 12)$, or $I_5 = 6.04$

With fault at A we know that generator 3 with 10 per cent inherent reactance will give 10 times normal rated current.

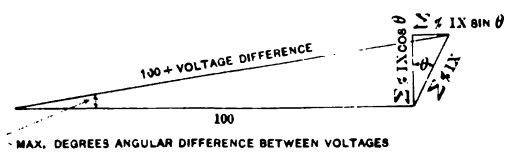
Therefore, raising all the current values by the ratio of 10/6.04 and noting that from symmetry, the current over reactance

c is the same as that over reactance b, we get the short-circuit current at $A = \frac{10}{6.04}[(2\times3.2) + 6.04] = 20.6$ times normal rated current of one generator.

Following the same process we get $I_9 = 48.7696$, but knowing $I_9 = 10$ times normal rated current of one generator, the actual short-circuit current at $B = \frac{10}{48.7696}(48.7696 + 26.368) = 15.4$ times normal rated current of one generator.

The current flowing in the various portions of the busbars as shown in Fig. 8, is obtained by finding points on the ring bus from which there are two symmetrical paths of equal reactance to the transfer bus, and considering that the current not sent out direct from the generators over the feeders follows these paths to the transfer bus.

The curves of Figs. 6, 7 and 10, are obtained by first drawing the diagrams and obtaining the current values as shown by Fig. 8. From these diagrams are found in each case the maximum value of $\Sigma I X$, between any two feeding points on the busbars. For example, referring to Fig. 8, with six machines running the maximum $\Sigma I X = \frac{1.5}{9} X + \frac{4.5}{9} X = \frac{6}{9} X$. By referring to the other eight diagrams in this figure it will be seen that $\Sigma I X$ is maximum with six machines running. The voltage difference and the degrees angular displacement between voltages are then found by the following diagram:



A very slight error is introduced by considering $\Sigma I X$ a straight line, because, in reality, each component has a slight angular displacement from every other component. The effect of this error on the curves is, however, unappreciable.

DISCUSSION ON "PROTECTIVE REACTANCE IN LARGE POWER STATIONS" (LYMAN, ROSSMAN AND PERRY), NEW YORK, FEBRUARY 25, 1914.

Philip Torchio: The authors have assumed that the generators have 10 per cent internal reactance, and some of the curves have been figured on that percentage. Although there may be modern machines that are being designed with the object of high internal reactance in view which have an internal reactance as high as stated, the great majority, or practically all of the machines in central stations at the present time, have internal reactance considerably smaller than 10 per cent. On 25-cycle machines the internal reactance will be 5 per cent or less. In such cases if you had assumed 5 per cent internal generator reactance, the figures and curves presented would have been considerably different and would have shown that there is little gain in installing bus reactances in excess of 12 to 15 per cent.

This large amount of reactance in bus sections is somewhat of an objection in most of the conditions where you have the feeders radiating from the different sections of busbars into substations and being multiplied in the substations, since these parallel feeders form a shunt to the reactance. If you have three sections of busbars divided by 20 per cent reactances, and feeders from these buses paralleled on substation buses, if you have trouble on one section, the protection that you get from this 20 per cent reactance is minimized by the impedance of the shunting of these feeders, and the effectiveness of these high reactances will be reduced to 12 to 15 per cent.

The authors point out the difficulties of having these reactances too high on account of having a phase displacement across the reactance which is shunted by feeder circuits and causing currents to flow through these by-paths. I do not think the paper covers fully the size of the reactances required, as they consider the bus reactances capable of carrying full-load current of one generator only, and the per cent rating is made on that basis; at least, that has been the practise followed by a number of engineers. I think it is a mistake to put in a reactance in the busbar that has less current-carrying capacity than the capacity of the switch which you put in for that connection. That is, if you put in a 1200-ampere switch to connect the busbars, the reactance which is in series with the switch should have a continuous carrying capacity of 1200 amperes.

I think the two points I make would tend to bring about a rather small reactance per section, that is, the per cent reactance, rated in the function of the carrying capacity to the switch, which I imagine usually is determined by the amount of maximum power you expect to transmit on that line from one section to another.

I regret that the paper does not cover the field of feeder reactances as fully as the busbar reactance, although it has been mentioned to some extent. It would have been quite an addition to have a complete treatment of the feeder reactance, which is, I think, one of the greatest mediums for securing protection of our high-tension systems.

W. S. Moody: The principal requirement of such reactance is that it shall be extremely safe and substantial. It is put in to protect at times of extreme trouble, and unless it is absolutely able to handle trouble within itself at such times, then perhaps it had better not be there at all. The heavy forces that have to be taken care of in the magnetic strains and the tremendous amount of power that has to be absorbed momentarily, all require the greatest rigidity and the greatest simplicity, and unusual factors of safety in every respect, in such a device.

With reference to the use of reactances, rather than the devices themselves, it seems to me there are two broad considerations that we want to remember. One is that all power these days is distributed on a constant-potential system. Consequently, an amount of reactance that interferes appreciably with maintenance of constant potential is prohibitive, but, on the other hand, we cannot have too small an increase of current at times of trouble and short circuits. Consequently, the amount of reactance and the location of the reactance, so long as they do not interfere with the maintenance of constant potential, cannot be used too freely, because even if the apparatus is quite capable of standing short circuits the operation of the system is that much less disturbed, to the extent to which the current at the time of trouble can be limited. So, outside of the financial consideration of the cost of the reactance, too much reactance cannot be introduced, in the sectionalizing of a system, so long as the maintenance of approximately constant potential is not interfered with.

Henry G. Stott: This is a subject which has been brought to our notice very strongly in connection with the redesigning of one of our plants, and also in connection with the introduction of large turbo units having a normal capacity of 30,000 kw. each. We went at the problem as from the point of view of trying to protect the generator from the cables, and to protect the generators from one another, and we ended up by trying to protect cables from the generators. The problem, therefore, was entirely transposed. The generator is pretty well able to take care of itself, but the instantaneous currents, which are reached through the normal action of having a number of these machines (we used five in our calculations) in multiple on the busbars, feeding out to a number of substations, with five and seven feeders in parallel, rise to such enormous values, going up to about 60,000 or 70,000 amperes at 11,000 volts, that we immediately began to foresee trouble due to the repulsion and attraction between phases. The

calculations showed, with three-conductor No. 000 feeder, subject to short circuit of 60,000 amperes, that the dynamic repulsion between conductors per running foot (30.5 cm.) was over one ton. That was one phase of the problem which rather startled us, but we were even more startled by finding that the calculation showed very high temperatures would be reached before any oil switches so far made, could be opened. We assumed the oil switch could be opened in 12 cycles, on a 25-cycle system—it did not seem safe to assume it would go out faster, on average operation—and we found that in the period of 12 cycles, or less, the temperature rise on such a cable would be over 500 deg. cent.

These are the things which forced us into the use of reactances, and, of course, it is quite obvious that the insulation

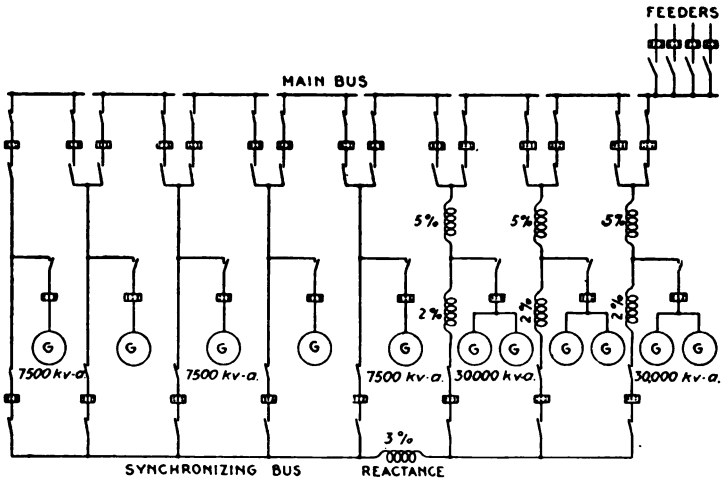


FIG. 1

of the cable would be partially destroyed by even one or two short circuits under these conditions.

We have adopted a scheme slightly different from any of those suggested in this paper, and it is shown clearly in Fig. 1, herewith. The bus normally is open, so each unit feeds out independently; but they are held in parallel through the reactances. As the load falls off, so that one of these units is sufficient to carry it, you close the bus junction switches and shut down the machine. The result is that there is no more reactance in one section than in another. The short-circuit currents in this arrangement work out very advantageously, also; the last calculation showed maximum short-circuit current of not more than 20,000 amperes, which is quite a contrast, compared to 60,000 amperes. We were forced into the use of reactances, not for the sake of protecting the machine, but to protect the

cable from the heating effect and the dynamic results of repulsion on the feeder.

The design of the reactance I think is quite important. It should be one which, as Mr. Moody said, is extremely substantial and practically indestructible from the heat point of view. That is a question yet to be settled, whether it will stand the shock and the high temperatures which will result on certain combinations. The ideal solution of the question we found was in use of individual reactances in the feeder, and we found also, as the result of that discovery, that we would have to build a separate plant to hold the reactances, and that did not seem to be quite feasible at this time, considering the present value of real estate. So the scheme shown is simply a compromise between bus reactance and individual reactance in each feeder, but I think there is no doubt that the ideal solution is an individual reactance in each feeder, and none in the station. However, in large cities that is obviously out of the question, where real estate and buildings are so expensive.

Paul M. Lincoln: There is one point, in regard to the use of reactance, which in a great many discussions is lost sight of, and that is the transient period. If we assume 10 per cent reactance, and 100 per cent voltage, the maximum instantaneous current which can flow through the circuit is not ten times full-load current, but twenty times. If you hit the wave in the right place you will get transient conditions which will give twenty times full-load current. It rapidly goes down to ten times full-load current. If one takes account of transient conditions he gets twice as much current as he will under steady conditions.

Taking time along a horizonatal line, it is well known that during the transient period the voltage waves will become symmetrical, around a logarithmic curve, that is, asymptotic to the X axis, the greatest departure of the logarithmic curve from the X axis being just exactly the full voltage.

That is a condition which, unfortunately, most writers on this subject do not take into account. When, for instance, the authors of this report say so many times full-load current of one generator, we do not know whether they mean to take into account the transient condition or not, but if they do not consider the transient condition, it is easily seen that the worst condition may give a current as high as double the value which is named.

I believe that we all, after we have analyzed this problem, will take exactly the same attitude that Mr. Stott has taken. The intention at first invariably was to get something to protect the generators, because it was the generators which suffered in the early days. Now, we have gotten around the generator, know how to protect it, how to build a generator so that it is self-protective, and now the problem is to protect the service from the rush of current which comes out of the generator. It is now the service that needs the protection, and not the apparatus, and if

we bear that in mind in the study of this problem I believe it will throw a great deal of light on it.

V. Karapetoff: I was glad to hear Mr. Lincoln mention the transient period of short circuit, because I have felt for some time that we must not allow the generator to exert its full destructive action the very first instant of a short circuit, but must provide something within the generator to take care of this transient condition. The natural thought occurred to me to provide something in the exciting circuit, because the exciting circuit is smaller and lighter than the main circuit.

The most natural solution is to put additional reactance in the exciting circuit. Last week, I asked one of my assistants to make some tests, and while the tests were rather crude, because we had no oscillograph, and merely watched the instantaneous deflection of an ammeter, nevertheless, I think the results clearly show that reactance in the exciting circuit limits the first rush of current and is, therefore, useful. The size of this reactance is much smaller than that required in the main circuit, and what is more important, there is no objection to using iron in this reactance.

We used a small alternating machine in our experiments, and the normal value of the exciting circuit was 2.5 amperes. When the machine is short-circuited under certain conditions, and no reactance is put into the exciting circuit, the instantaneous exciting current (not the armature current) rises from 2.5 to 5 amperes. With sufficient reactance, the increase in the exciting current is only from 2.5 to 4 amperes. We also found a similar reduction in the armature current. The steady value of the short-circuit current, the value which occurs after a few instants, was 75 amperes. Without reactance in the exciting circuit, the instantaneous deflection of the ammeter was as high as 180 amperes, instead of 75—the ammeter first goes to 180, and then goes back to 75, due to that transient condition. With the reactance in the exciting circuit, the deflection is only 144 amperes, that is, it goes to 144, and goes back to 75.

It seems to me that here is a remedy which may be useful, not in replacing reactance in the sections of a-c. buses, but helping, at least, to reduce their size. In other words, I believe that it is not right to leave the generator to exert its full destructive action, but that provision must be made in the exciting circuit to limit this transient phenomenon by a sufficient reactance. If some kind of a constant-current regulator could be introduced in the exciting circuit, with a sufficiently quick action to prevent these sudden rises, then we could not possibly have these rises in the armature circuit, and consequently we would have less destructive action. In Dr. Steinmetz's book on "Electric Discharges, Waves and Impulses," there are several oscillograms given, showing what happens in the first instant of a short circuit on an alternator. The armature current rises instantly to a value much higher than its steady value, and the field current also goes

up, and is an oscillatory and pulsating current. We would not have these oscillations in the armature current, if we could prevent oscillations in the exciting current.

Harry R. Woodrow: I think Mr. Lincoln exaggerated a little the instantaneous rush of current on short circuit. The equation for this current in an inductive circuit is

$$i = \frac{E}{Z}\left\{\cos(\theta-\theta_0-\theta_1) - \epsilon^{-\frac{r}{x}\theta}\right\}, \text{ where } \theta_1 = \tan^{-1}\frac{r}{x}$$

and θ_0 is the angular phase of voltage at start of short circuit which must be at point of zero voltage to give maximum value of the transient term where X/r is large. Hence it requires π radius of electrical time for the transient term to reach its maximum value.

In the time π the transient term $\epsilon^{-\frac{r}{x}\theta}$ drops, so that the maximum peak is considerably below twice the normal. In addition to this, the generator voltage is materially reduced in the time π. From a number of tests on turbo-alternator short-circuits, we have found that the maximum transient peak will not exceed the normal peak by more than 50 to 60 per cent.

It is necessary to protect the generators, circuits, etc., at the time of this high initial peak which occurs in one-quarter to one-half a cycle, as any damage that is to be done is done at the time of maximum peak and hence no shunted resistance or reactance could be put in circuit quickly enough to do any good.

The last speaker recommended the insertion of reactances in the field circuits of generators. Punctures of generator field circuits now occur at times of generator short circuits due to the high voltage. Inserting an additional reactance in the field circuit to permit the field to be blown out within the first quarter of a cycle to reduce the current to one-half of its former value would require a reactance equal to the inductance of the field circuit and would produce a voltage approximately as high as pulling the field circuit without discharge resistances.

Feeder reactance will give by far the greatest amount of protection against the trouble which occurs in feeder circuits, and by far the largest percentage of the troubles will occur in feeder circuits. In the tabulation the authors speak about the reactance limiting the current to 30 times the normal rated full-load current of one generator and they have something like 5000 kv-a. required for the best condition of reactances between adjacent generators. If reactances were installed on feeder circuits of the same system, two-thirds per cent reactance would be sufficient to limit the current to 30 times the full-load current of one generator, which would require about 1500 kv-a. in reactances or less than one-third the amount of bus reactance. This per cent kv-a. saving depends on the

size of feeder circuits, and is proportional to the ratio of size of generator to feeder units.

Cassius M. Davis: The paper under discussion considers an ideal case, namely, where a new generating station is to be put in, and arrangement can be made at the time of installation to lay out the system properly to get the maximum protection. There is one difficulty which usually confronts the engineer on a system which already is in operation and growing; that is, the system may have been laid out some years ago with no anticipation that it would grow to such large capacity; the feeders may be connected to the busbar in a more or less haphazard fashion, and in order thoroughly to protect the service at the various substations several feeders may be run in multiple to substations. As a consequence the system becomes so large that it is necessary to protect it by sectionalizing, and the difficulty arises in placing the reactances so as to get the greatest benefit. With a new system which has a large number of relatively small-capacity generators, or if it is a very large system, where there are a number of large generators, it can be laid out very advantageously along the lines which have been shown in this paper. A much more difficult proposition is the system which has been in operation for some time using small units, when it is decided to replace the small units with much larger ones. The feeders and the feeder switches have been designed and installed merely to carry the feeder current. Now, if the larger units are put in, the currents at time of short circuit are very much larger than previously, and therefore it is necessary either to equip the station with new switches or to protect the system in such a manner that the old switches will be able to take care of short circuits, or, as in the case Mr. Stott has brought out, it is a case of protecting the feeders.

A number of cases like this have recently come up. It has generally worked out that the best arrangement of reactances to give the best protection is a combination of generator and feeder reactances, rather than bus-sectionalizing reactances.

Mr. Stott's illustration (Fig. 1) is a combination of feeder reactances and what we may call synchronizing reactances. Each group of feeders is protected by a single reactance. Then the generator is connected without reactance, and each generator is maintained in synchronism with the others in the station by what may be termed a synchronizing reactance and synchronizing bus. It is purely a case of group feeder reactances, no generator reactance, and a section reactance primarily to keep the generators in synchronism. The station would operate just as well without the synchronizing reactances, the protection would be practically the same, but for reasons of convenient operation the synchronizing feature becomes necessary.

Allen M. Rossman: Mr. Torchio remarked that our assumption of 10 per cent generator reactance was rather high.

We will admit that if we were working up the data for some of the older stations it might be high. But when we worked up these curves, we were planning a new 60-cycle station, and had no difficulty in getting guarantees of 10 per cent reactance in the generators, and so we based our curves on that value.

Mr. Torchio suggests selecting busbar reactances with an ampere rating the same as that of the oil switches in the busbars.

If you will refer to the diagrams in Fig. 8 of the paper you will find a close approximation to the required current rating. We have assumed one generator, two generators, three generators, etc., up to nine generators in operation, each carrying its full rated current. We have assumed that this current is fed out in equal amounts from each of the nine feeders or group feeders. You will find by glancing over the diagrams that in no case do we get higher than five-ninths of the full-load current of one generator through any reactance. This figure, with an allowance for unbalance of feeders, gives the proper current rating for the reactances as well as for the bus section switches.

Mr. Stott has stated that in installing generator reactances at an old station another building might be needed to accommodate them. The space required and the high cost are, I think, the chief objections to the extensive use of generator reactances. Reactances in the generator leads are, in my opinion, best adapted for the protection of the generators themselves, but with the generators that we are buying these days it is not so necessary to provide additional reactances in their leads, because of their high inherent reactance and their improved mechanical construction.

Mr. Woodrow has commented on the question of transient effects, raised by Mr. Lincoln, and I will not say anything further on this subject. The method of deriving the curves, as shown in the appendix, considers only the Ix drop.

Mr. Davis has made some comments about stations which were designed some years ago, and on further growth required the addition of reactances. I might mention that not many of the large city stations built a few years ago were designed to deliver the amount of power we are calling on them to give today, and the application of reactances to these stations may be considered special cases. These older stations designed perhaps ten years ago, or even seven or eight years ago, have to give way to new stations, and it is the application of reactances to these very large stations that our paper is intended to cover.

Referring to Mr. Davis's question as to the rating of the reactances, the rating of the reactance is based on the current times the voltage. If we double the current we get double the voltage, because we have twice as many ampere-turns, and therefore we get four times the reactance, therefore the rating varies as the square of the *current.*

O. J. Ferguson (by letter): Last summer I had occasion to study the various results to be obtained by putting reactors of various capacities in buses and feeders, with straight and ring buses. Based upon 10 per cent inherent reactance of generators, my general conclusions were as outlined below. It will be seen that they agree in many particulars with those of the paper we are discussing.

1. Additional generator reactors are not necessary.
2. The most effective method of placing reactors is to distribute them in buses and in feeders.
3. Based upon one-half the normal output of a bus section, a 25 per cent reactor is generally sufficient for the bus.
4. A 3 per cent to 5 per cent reactor is advised for feeders.
5. If generators with 10 per cent reactances are fed to buses through transformers having 6 per cent to 8 per cent reactance, the bus reactors may be of lower reactance.
6. It is feasible to install bus reactors of impedance sufficient to sustain synchronous apparatus on bus sections adjacent to the one upon which the fault occurs.
7. Owing to the demands of light-load operation, switches to bridge the bus reactors should be developed and made interlocking with the generator switches so that they cannot remain closed when the reactance is required.
8. The present method of rating a reactor is not wholly successful.

As regards the reactor rating, it is worthy of note that reactors to be placed in feeders or in generator leads present a very reasonable demand that they should be rated in terms of those units.

When bus reactors are used, they are frequently rated in terms of only a part of the normal capability of the adjacent bus section, as, for example, upon the basis of only one of the two or three connected generators. This is only a "local" rating and may lead to confusion and to incorrect comparisons of data, etc.

It is my belief that, inasmuch as reactors are subject to installation under such indefinite conditions, they might well have, beside their specific or local rating, a fundamental rating in terms of volts reactance per 100 amperes at normal frequency. This could be called the "60-cycle reactive constant" of the device.

Alex. E. Bauhan (by letter): The paper gives considerable attention to the subject of voltage differences existing in the various sections of a bus equipped with reactances. This voltage difference of course is ordinarily a very undesirable feature, but under certain operating conditions becomes a highly desirable feature. For instance, consider a hydroelectric system consisting of a generating station and two transmission lines having widely differing voltage regulations. Now it is evident that if flat voltage is called for at the substations and no synchronous condensers are available, it becomes necessary to operate the two transmission lines separately at the generating station end, which is usually undesirable.

However, if the two systems are tied together through a set of reactance coils it becomes an easy matter, by properly adjusting the load and excitation, to regulate the voltage on one system independently of the other and yet keep them in parallel.

This scheme is now being used on a high-voltage transmission system under similar conditions to the above. The regulation of one of the lines is 10 per cent at a maximum load of about 65,000 kw., and that on the other line is about 2 per cent with a maximum load of about 4000 kw. The generators are of about 10,000 kw. each. It is desired to give constant voltage at both substations, and as it is necessary to parallel the two systems at various times during the day, to make full use of the generating capacity, the voltage disturbances were very objectionable. However, by making use of bus reactance, which has already been installed, it is possible to operate these stations in parallel at any time, each system getting its proper voltage regulation.

This is a point which may not be of particular value in city distribution work, but may be well to keep in mind in connection with the operation of more extended transmission systems.

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OUTDOOR VS. INDOOR SUBSTATIONS

BY ALEXANDER MACOMBER

ABSTRACT OF PAPER

The development of the outdoor substation vs. the indoor type is an interesting commentary on the adaptability of engineering progress to new fields and the subject is briefly recapitulated in this paper, in line with the developments and application of this branch of transmission work.

The causes for development of this apparatus, together with a general description of the classes of apparatus involved which have been changed to meet new conditions, are given. The application of the indoor vs. the outdoor substation to services of different character is indicated, and the tendencies for the future briefly touched upon. A comparison of the advantages and disadvantages of the types considered is outlined.

In general, it appears that the equipment for outdoor installations has been successfully developed to meet the severe conditions imposed, and the numerous installations involving outdoor features indicate the extensive use of this idea in the future, while its development as applied to the central station itself affords a considerable field for attention.

THE DEVELOPMENT, in the last half-dozen years, of the outdoor substation vs. the indoor type, with its attendant problems, is a most interesting commentary on the adaptability of engineering progress to new fields. Primarily, as in most such cases, the cause was an economic one, the desire to serve from transmission systems the small consumer who could not be reached on account of the excessive first costs of installation.

The development of suitable apparatus to meet this fundamental condition has opened up a new field for substation development, and progress along engineering lines necessitated by new and peculiar conditions has indeed been remarkable. These problems, especially in reference to the class of work which introduced them, have been well solved, but the possibilities in application to larger and broader fields has meant attacking problems of a far more complex nature. The success obtained justifies the expectation that outdoor substations will occupy a very important position in the development of transmission work. The extent, however, to which it is desirable to develop these propositions, must receive serious consideration dependent

on the engineering features of design and operation, and fundamentally on the economics of the problem.

This matter has been ably discussed previously, but its importance is such that it is proposed briefly to recapitulate the subject in view of its developments and possible applications, trusting that discussion of practical experience will be afforded.

Development of Equipment

To meet the engineering conditions of outdoor operation, considerable experimental work has of course been necessary, and results indicate that there is nothing inherent in the requirements of apparatus for these conditions which apparently cannot be successfully met.

The classes of apparatus involved which have required development to meet new conditions may in general be grouped under (1) protective equipment, (2) transformers, and (3) control equipment.

Protective Equipment

The most important protective apparatus affected by outdoor installation is the electrolytic lightning arrester, which offers the most complete protection available at present for high-tension lines. Heretofore it has been necessary to protect this equipment by housing, but the development of low-temperature electrolyte, together with other details of design, makes it now feasible to place the entire equipment out of doors, even under the most severe climatic conditions. The winter season when the severest temperatures are encountered, is also, as a rule, free from lightning disturbances, though it is important to secure continuous service of protective devices of this nature on account of surges occurring on the lines, the necessity being particularly noted where the switching of the high-tension systems is liable to cause serious line disturbances and consequent breakdowns at weak points. It is as much the function of the arrester to absorb these disturbances as to avert the direct effects of lightning itself.

Transformers

The operation of outdoor transformers is no longer experimental. The principal difficulty to be met is the climate, with its changes in temperature and atmospheric conditions. In general the outdoor type of transformer is similar to the indoor type except that the cover and leads are designed to shed moisture and provide the necessary higher factors of safety.

Both self-cooled and water-cooled transformers are applicable to this service, with due consideration of its requirements. In the former case, grades of oil suited to the conditions are of course necessary, the only serious difficulty being on account of possible freezing. As a rule the load of the transformers will keep the oil sufficiently warm, but it is important that precautions be taken in order to prevent condensation of moisture. If necessary this is accomplished by small heating coils installed in the tops of the transformers. The freezing of the oil itself in idle units or under severe conditions may also be guarded against by the installation of external heating devices under the casings.

This freezing of the oil may be serious, particularly if transformers are out of service, because on energizing them, dissipation of heat, with the oil frozen, is liable to be slow, and inasmuch as the temperature rise in large units is about 20 deg. cent., the windings might be injured before the oil is liquefied. Little trouble is experienced, however, as ordinarily oil will not freeze at a temperature above −15 deg. cent., and special grades solidify at a considerably lower point.

The use of water-cooled transformers involves similar precautions against moisture, with the addition of suitable protection to the water circulating system, although the water of itself, by its circulation through the transformers, would not freeze except under severest conditions, provided the external connections are properly protected.

There apparently has not been much experience with air-blast transformers out of doors and it would seem that there might be a field for them as they do not offer the difficulties in giving climatic protection which are encountered with other types of transformers, provided moisture is kept out; and the cost would be less.

Control Apparatus

The design of control apparatus, such as switches, circuit breakers, etc., has also met the severe conditions imposed, and outdoor switches of extremely high voltage are operating satisfactorily in severe sleet and snow storms. As with the other apparatus, the general indoor types have been made suitable for outdoor service by perfection of details, such as enclosing the mechanisms, motor control, etc.

In general, then, it may be fairly stated that the use of the outdoor substation is not to be limited particularly by the lack of apparatus suitable for the severe operating conditions, and

it is certain that even greater steps in the improvement of apparatus of this nature will occur.

Application

The indoor substation has been highly developed to meet the various classes of service imposed upon it, and in fact has become very nearly standardized. It is hardly necessary to consider its development and status here, except as a comparison with those particular classes of service in which the outdoor substation may appear as its competitor, the advisability of the latter depending on a careful consideration of the various advantages and disadvantages as compared with the established type of indoor substation.

Generally speaking, for the purposes of considering outdoor installations, substations may be classified as serving the requirements of (a) small isolated loads, (b) large capacity loads, and (c) apparatus auxiliary to central stations.

A brief discussion of these respective divisions will indicate some of the requirements and opportunities incidental to each.

Small Isolated Loads

It was in the class of small isolated loads that the development of the outdoor substation first started, and this has afforded its greatest field to date.

Complete outdoor installations up to a few hundred kv-a. have enabled service to be given to isolated customers and small communities which otherwise could not be profitably served directly off the main transmission lines. It is possible to locate such substations almost anywhere, the structural and foundation requirements varying with conditions. The simplicity of design and construction has meant a small investment and a minimum of operating troubles. High-tension switching is usually limited to air-break types, instead of the costly oil switches, while lightning protection is afforded either by the electrolytic lightning arrester or the cruder horn type. Most such installations have been free from elaborate secondary control, that provided being, if any, of the simplest type, established in weatherproof housings. There can be hardly any question as to opportunities for this type of station, and its rapid adoption and extending installation, on account of the factors of simplicity, low cost and lack of attendance, indicate the importance of its field.

Large Capacity Loads

The application of the outdoor substation to large capacity installations, particularly where the secondary control is split up into various circuits with more or less auxiliary apparatus, confronts us with larger problems. The substation may combine not only the functions of a switching station, but also that of supplying a large load to a community, and in general its location would not be affected by the type adopted, provided sufficient space is available.

With substations of this character, involving attendance, it is necessary to provide a suitable building designed for at least part of the installation. What part of the high-tension apparatus may properly be installed out of doors depends largely on the saving thereby effected. The actual outdoor apparatus must be provided for separately, and a combination of the indoor and outdoor substation will in many cases prove most advantageous. In some cases it is feasible to place the whole outfit out of doors, including the low-tension control equipment, provided the latter is not extensive, but in most cases it is questionable whether the operating features will permit this extreme. In cases where attendance is required it is certainly advisable to install the secondary equipment indoors.

The manner of installing the outdoor equipment will, of course, depend upon the size and importance of the layout. In general the incoming and outgoing lines must have proper terminal structures for connection and distribution to the banks of transformers. The transformers themselves should be provided with proper foundations, preferably of concrete, so designed that they may be removed on rails, and provision should be made for heating the cases if climatic conditions require it, while the piping for oil or water must be carefully considered.

The installation of lightning and control equipment is also subject, in general, to the same requirements.

A most important detail of the outdoor installation is that of providing proper facilities for repairing damaged apparatus, and large stations must provide some shelter where such repairs can properly be made.

The space occupied by the outdoor installation will, of course, be large, and adequate provision must be made for preventing anyone from coming in contact with the equipment.

Apparatus Auxiliary to Central Stations

Many central stations operated in connection with transmission systems have a considerable portion of their buildings given up to high-tension equipment and apparatus incidental to its operation.

The outdoor installation of such latter equipment would, in many cases, reduce the building cost materially, provided the extra outdoor space is available. The features of installation would be similar to those noted above. This phase of outdoor application is worthy of considerable attention and study.

Comparisons

Considered generally, the following are the advantages and disadvantages of outdoor installations:

Advantages	Disadvantages
Lower first cost	Repairs
Ease of extensions	Operating risks
Reduction of fire hazard	Danger to public
Simplicity of layout	Appearance.

Reduction in cost was the cause for the development of this type of construction, is the reason for its continuance, and will govern its extensive application, when properly interpreted. For the small isolated substation of a few hundred kv-a., the cost will be from 25 per cent to over 50 per cent cheaper than the corresponding indoor station. For large installations, particularly where a building is provided for secondary control, the per cent of saving is much smaller, the less being the cost of the outdoor part of the installation in proportion to the total, the less being the saving due to this construction.

In connection with the cost, reduction of fire risk is important and outdoor service reduces this to a minimum.

The simplicity of either complete or partial outdoor installation is particularly attractive. With the intensive development of the indoor station we have succeeded in obtaining about all the elaborateness of design possible, and any development offering opportunity for simplicity of construction and operation should be welcome.

The disadvantages outlined have been mentioned generally in passing. The most serious ones are those of operation and facility for repairs. Experience indicates that operating difficulties are well overcome, and generally speaking, damage to modern apparatus is reasonably rare. Danger to outsiders can

certainly be prevented by fencing, etc., while the matter of appearance is only of interest in certain localities.

Summary

Summarizing the situation, we find that the equipment for outdoor installations has been developed to meet the severe conditions imposed. Successful operation of installations of this character during several years shows that operating difficulties are unusual.

It is significant that at present there is installed, or under construction, approximately 300,000 kv-a. in high-tension outdoor type transformers. The query may well become, instead of "when shall we use the outdoor substation?" rather "when shall it *not* be used?" The cost is the main factor, although operating features with increasing high voltage become attractive on account of the simplicity of the layout and the tendency to make the high-tension equipment a part of the line itself.

The development of these ideas when applied to the central station itself should be as marked as it has been in the case of the substation, although the limits desirable to impose must in all cases be determined by the particular problem under consideration.

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OUTDOOR SUBSTATIONS IN NEW ENGLAND

BY FRED L. HUNT

ABSTRACT OF PAPER

The present development of outdoor switching apparatus and transformers for systems of 110,000 volts or less is such as to make their use entirely successful, and in most transformer substations, a considerable saving in first cost can be accomplished without increase in operating expenses, by making use of this type of equipment.

This paper gives a brief description of two substations of 10,000 kv-a. ultimate capacity, just put into operation, in which all the high-tension switching apparatus (66,000 volts) and the transformers are outdoors. The low-tension apparatus (13,200 volts) and the railway apparatus are indoors. This arrangement is based on the three following principles which have in this case proved to be sound:

1. That the greatest saving in building cost can be made by putting all high-tension work outdoors.
2. That the switching apparatus, lightning arresters and transformers of voltages in the neighborhood of 66,000 volts are practical and may be successfully operated outdoors in New England.
3. That distributing switchboard, control switchboard and railway apparatus and switchboard are not suitable for outdoors.

DURING the past summer, there have been built and put into operation by the Amherst Power Company two substations, a brief description of which may be of interest in connection with the present tendency towards the use of outdoor substations. One of these is located at Chicopee and one at Agawam, Mass., both being supplied from the company's double-circuit, 60-cycle, three-phase, 66,000-volt transmission line extending from Turners Falls to Springfield. The accompanying illustrations show various views of these substations, which are practically duplicates as far as general layout is concerned.

When these stations were being laid out, considerable attention was given to a study of the advantages and disadvantages of indoor and outdoor apparatus, the result of which was the adoption of what might be called a semi-outdoor substation in which all the 66,000-volt equipment, including the step-down transformers, was placed outdoors, as were also the aluminum lightning arresters on the 13,200-volt outgoing lines, while the

13,200-volt buses and switching, the control switchboard, the 2300-volt distributing switchboard and the railway apparatus were placed inside.

The choice between indoor and outdoor apparatus in different parts of the equipment was based on the following considerations:

1. The 66,000-volt apparatus was the most bulky part of the equipment, and therefore the greatest saving in building space could be accomplished by putting it outdoors.

2. The more complicated switching necessary with the numerous 13,200-volt and 2300-volt outgoing circuits and synchronous motor circuits would have been much more difficult and expensive to handle in an outdoor installation. Hence, they were placed inside.

3. The control switchboards, with their metors, instruments and storage battery, and the railway motor-generator sets, have not at the present time been developed to the point where it is practical to operate them outdoors; therefore these were placed inside. Except in the case of the switchboards with their meters and instruments, the storage battery and the railway sets, none of which are suited to outdoor operation, the relative location of the remainder of the apparatus, that is, whether it would be placed indoors or outdoors, was determined principally by comparison of estimated first costs, since no well-founded objection to the use of outdoor aluminum lightning arresters, oil switches, transformers or buses could be found.

The saving in the first cost of the building may be arrived at very closely on the basis that the cost of two proposed buildings, erected on the same site, for the same purpose and of the same general design and material, will, within reasonable limits, have first cost in the direct proportion to their cubic contents. A building, similar to the one actually erected, but of the dimensions necessary to accommodate indoors all the apparatus, including the 66,000-volt equipment, allowing for the same switching scheme, and providing a space for future expansion equal to that which is incorporated in the present station and outdoor foundations, would cost on the above basis 202/86ths of the cost of the present building. After allowing for the extra cost of outdoor apparatus and the cost of outdoor foundations and steel structures, the saving in this case was an amount equal to 11 per cent of the cost of the complete station and equipment as built.

The general arrangement at the Chicopee substation (see

Figs. 1 and 5) is as follows: A tap circuit is brought in from each of the two transmission lines through choke coils, disconnecting switches, and solenoid-operated non-automatic oil switches to a transfer bus, from which the transformers are supplied through disconnecting switches and solenoid-operated automatic oil switches, one set for each bank. An aluminum lightning arrester is installed on each incoming line. At present there is one bank of three 1500-kw. oil-cooled transformers of the radiator type in use here, with one spare unit, and foundations and conduits are installed for a second bank. This type of transformer construction brings the cost of oil-cooled transformers for outdoor work down to a point where their increased cost over water-cooled transformers is so little that it does not pay to add the complication of water cooling for the small saving in first cost that can be accomplished, especially where the water would have to be pumped, as in this case, and where, as in all outdoor stations in the northern part of this country, special precaution must be taken to prevent the freezing of water pipes. From the transformer bank one circuit is carried underground into the building to the 13,200-volt double bus in a concrete bus structure.

The arrangement so far as outdoor station is concerned, is the same at Agawam (see Fig. 2) except that there is a difference in the capacity of transformers, and there are two circuits from the secondary side of the transformers into the building; one leading to the 13,200-volt bus, and one to the 2300-volt bus, as power is distributed at both voltages from Agawam station.

Attention may now be called to some special features of the outdoor equipment. The oil in the outdoor transformers freezes at -15 deg. cent. It is therefore necessary to keep the temperature of the oil in the spare transformer above this point if it is to be ready for immediate service. This will be accomplished by connecting the spare transformer to the bus on the low tension side, from about Jan. 1st to Mar. 10th of each year. During the remainder of the year the temperature of the oil in the spare transformer does not go down to its freezing point when left without artificial heat.

The transformers and oil switches are connected by a complete piping system to a two-compartment oil tank buried in the ground, so that oil can be drained from any transformer or oil switch into its respective compartment of the oil tank,

and from there can be pumped through a portable oil filter press back into the transformers or switches. Alarm thermometers on the transformers are connected to bells in the station. There is installed in the cover of each transformer a small heating unit taking 200 watts at 110 volts. The object of this unit is to keep the air in the top of the transformer, and especially the spare transformer when not excited, a little above the temperature of the air outside, so that in the process of breathing, which is sure to be present to some extent in any large transformer subjected to varying temperatures, the air taken in, even though heavily laden with moisture, will have that moisture vaporized by coming in contact with the warmer air inside, rather than being further condensed by coming in contact with cooler air inside, which latter condition would occur if there was no artificial heat inside the cover of the transformer.

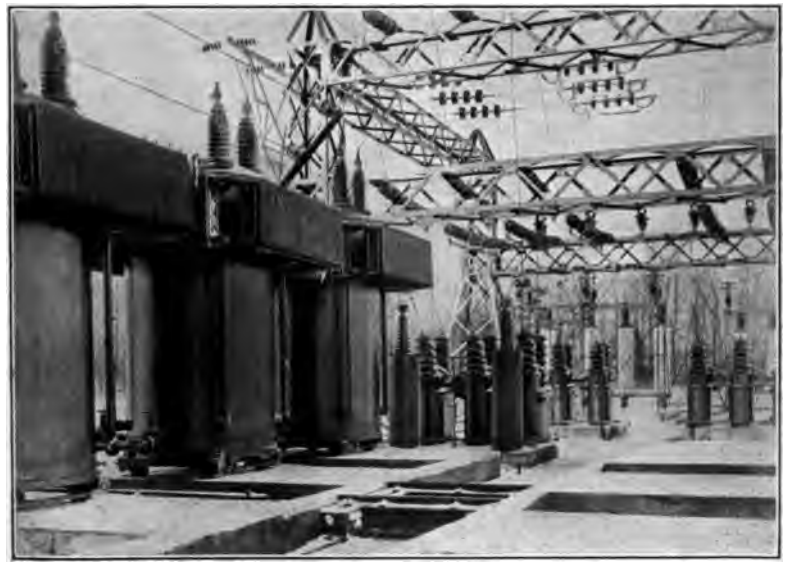
When it becomes necessary to disassemble a transformer it is rolled on to a transfer truck upon which it is run into a compartment at one end of the station where a hoist is available of sufficient capacity to lift and remove the core. Switch hooks used for operating the disconnecting switches outdoors are fitted with a copper cone at about the middle of the handle, which cone is grounded when the hook is to be used. All the outdoor aluminum lightning arrester cans are painted white to overcome a difficulty experienced in warm climates where the absorption of the sun's heat by dark-colored cans has raised the temperature of the electrolyte of the arrester to a point where it was damaged. Two coats of white paint on these cans have been sufficient to keep the temperature of the arresters below the danger point in these installations, up to the present time. This same treatment may be applied with similar results to the transformers where excessive temperatures are reached on account of the sun's direct rays.

The winter weather test of these substations has already begun and the results so far observed are satisfactory. The Chicopee station after a recent sleet storm is illustrated in Fig. 3.

Each outdoor station is surrounded by an iron picket fence and all the equipment is set on concrete foundations extending below frost line and about 15 in. (38.1 cm.) above the final level of the ground. Thus far in the operation of these stations nothing has occurred which indicates any important point of disadvantage in the outdoor arrangement, except that some difficulty was at first experienced in keeping the joints of the

FIG. 1—GENERAL VIEW—CHICOPEE SUBSTATION. [HUNT]

FIG. 2—GENERAL VIEW—AGAWAM SUBSTATION. [HUNT]



[HUNT]

FIG. 3—OUTDOOR APPARATUS CHICOPEE SUBSTATION.

[HUNT]

FIG. 4—OUTDOOR SUBSTATION AT CONSUMER'S PLANT—750-KV-A. TRANSFORMER BANK, 13,200 VOLTS TO 2300 VOLTS.

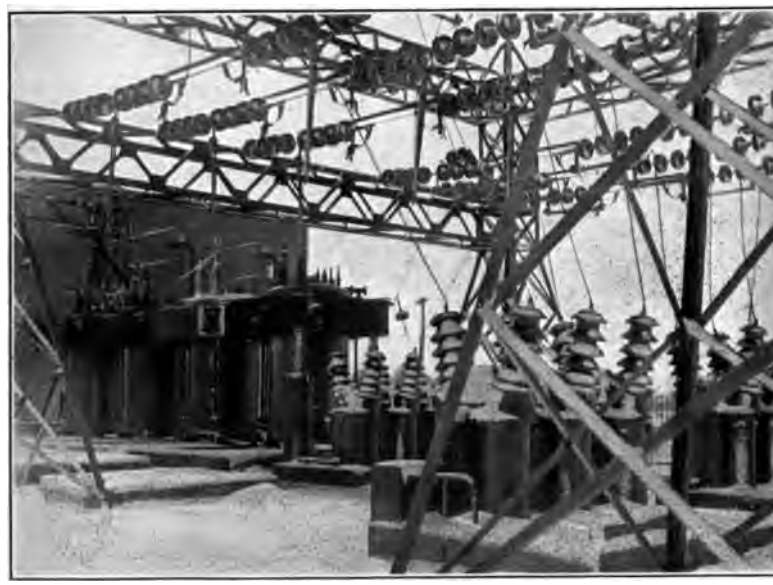


FIG. 5—CHICOPEE SUBSTATION AFTER SLEET STORM. [HUNT]

cooling radiators on the transformers oil-tight, due to the wide range in temperature to which they were subjected every 24 hours. The design of these radiators has now been changed, and the new radiators have thus far stood the test of wide temperature changes without developing leaks.

It is probable that in practically all substations of the same general arrangement as these, considerable saving can be accomplished by the outdoor arrangement of the high-tension apparatus, except where cost of land is very high, as in cities. There is no reason why, with proper local conditions, a considerable saving cannot be accomplished by the use of outdoor apparatus at generating stations. In other cases, the saving may be small or none when the particular arrangement of canal intakes and generator rooms is such that only a small additional expense is required to house the transformers and high-tension switching. Each case should receive special consideration. There appears to be no good reason for using outdoor apparatus except where a saving in first cost can be shown.

Outdoor apparatus is also used on this system at several of the consumers' substations, where power is delivered at 13,200 volts and stepped down to 2300, 550, 440 or other voltages. Fig. 4 is a view of a typical station of this kind where power is delivered at 13,200 volts to a bank of three 250-kv-a. oil-cooled, single-phase transformers, and stepped down to 2300 volts for use in a textile mill.

The transformers are connected to the 13,200-volt circuit through combination horn-gap arresters and choke coils, and horn-gap disconnecting switches, and the power is metered at 13,200 volts by the use of outdoor potential transformers, indoor current transformers under shelter, and a meter in a box with glass cover. The tower stands approximately 20 ft. (6 m.) high, the bottom of the transformers being about 10 ft. (3 m.) from the ground.

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INDOOR AND OUTDOOR SUBSTATIONS IN PENNSYLVANIA

BY H. L. FULLERTON

ABSTRACT OF PAPER

This paper covers some points in substation design for installations for the lower voltages, including choice of location, type of building and arrangement of electrical apparatus.

The subject is treated in three divisions, namely: customers' substations fed from the distribution system, customers' substations fed from the transmission system and company's substations. Attention is called to some of the advantages of both the outdoor and indoor substations for each of the different divisions.

Points to be considered in the selection of locations for substations are outlined and several types of buildings, particularly the one of concrete slab construction, are described. Attention is also called to different arrangements of electrical equipments, which may be employed for installations of various sizes.

Different schemes for installing high-tension switchboard apparatus are considered, attention being called to the open wire and the cell structure installations, with special reference to the concrete cell structure and the method employed in its construction.

THE OBJECT of this paper is to cover in a general way outdoor and indoor substations of voltages up to and including 20,000, the limit being drawn at 20,000 volts because, where a higher transmission voltage than this is used, it is necessary to transform to a lower voltage on entering centers of population. I intend to call attention to some of the main points to be considered in determining the best location for substations for various purposes, to show some forms of substation buildings which can be used under various conditions, to give some of the advantages of the outdoor and indoor types, and to show some forms of electrical installations which have been used to meet the various conditions which present themselves in substation design.

For convenience in handling the subject, I shall divide it into two general divisions:

1. Customers' substations, or those which are installed on

the customer's premises and used only for feeding his service. This will be subdivided into:

(a) Those fed from the regular distribution system.

(b) Those fed from the transmission system.

2. Company's substations, or those which are installed by the company at a center of load and used to deliver service at a reduced voltage to the consumers within that district.

Customers' Substations Fed from Distribution System

Unless the customer is along the line of a low-tension distribution system, it is necessary to install a substation to serve him with low-voltage service. This substation may be of any size from a small transformer on a pole on the street, to a large capacity installation in a regular substation room, depending on the customer's load. The probable demand of the customer determines the type of substation to be installed, and whether it be fed from the primary distribution mains at a medium voltage or from the transmission system direct, at the higher voltage. It is impossible to handle some of the larger installations economically from the primary distribution system, which is usually between 2000 and 5000 volts.

Customers whose demands are small, are ordinarily served by installing a small transformer on a pole adjacent to their load. This installation is very simple and serves quite well, until the demand requires transformers which are too large to be conveniently handled in this manner, but 50 kw. is probably about the limit for this type of construction. When the demand is above this point, it is necessary to make some special arrangement to furnish his service. If the location is such that room can be secured on the customer's premises, the transformers can be nicely installed on ordinary wooden poles something after the manner shown in Fig. 1.

In this arrangement two poles are placed on 10-ft. (3-m.) centers and a platform built between poles. A very neat arrangement can be made of the wiring on both the primary and the secondary side and the construction can be made safe both mechanically and electrically. The platform is constructed by fastening a channel to each side of the pole by through bolts and building thereon a wooden floor. The limit for an installation of this kind is about three 50-kw. transformers.

Where greater capacity is required, it is often possible to set the transformers on a platform on the ground, enclosing them

with a high fence, so as to guard against persons coming in contact with electrical apparatus.

If conditions are such that an outside location cannot be secured for the transformers, it is then necessary to procure an inside location and build a transformer vault or indoor substation. Of course, the customer wants the transformers located in the space that cannot be used for any other purpose, which is usually in the basement or sub-basement, and below the sewer level, while the rules of the National Board of Fire Underwriters require transformer vaults to be sewered, also ventilated to the outside air. It quite frequently happens that the building is nearly completed before the architect remembers that a transformer vault will be necessary, unless some representative of the operating company impresses very forcibly upon him the necessity of making provisions for the same. Then the only available location is in some out of the way corner, where the transformers must be taken in through important parts of the building, often down flights of stairs of costly construction and entirely unsuited for the passage of heavy apparatus. When a freight elevator is installed, it is usually so located that it is not available for handling the substation equipment.

If the architect has provided a transformer vault, it is usually about one-half the size that is necessary. In one particular instance that I recollect, the installed transformer capacity amounted to 1125 kw., while the space provided by the architect was 3 by 10 ft. (0.9 by 3 m.), in which he expected us to place both the transformers and switching apparatus. In case no vault has been provided, it is necessary for the operating company to make the installation, which must be made in accordance with the rules of the National Board of Fire Underwriters, hence, it is necessary for the company to construct its own transformer vault.

Fig. 2 shows a fireproof transformer vault which has been installed in a building in which the architect had failed to make provision for the transformers. This type of vault has given very good results, where used, and is quite pleasing in appearance and cheap and easy to construct. The vault is built up of concrete slabs 3 by 6 ft. (0.9 by 1.8 m.) and 2 in. (5 cm.) thick, and an iron door having similar dimensions. The slabs and the doors can be prepared in the shop at odd times and kept in stock for such cases. Two or three men can easily handle

these slabs and erect the transformer vault in a short time. A vault of this type of construction can be made in any size from 3 ft. by 3 ft. (0.9 by 0.9 m.) and 6 ft. (1.8 m.) high, up, in multiples of three. It is portable, being simply held together at the corners by small angles and can readily be moved in case any change is being made which requires its removal. The bolt holes, etc., in the slabs are cast in at the time of preparation. As will be noticed from Fig. 2, this construction furnishes a convenient place for mounting oil switches, instruments, etc., so that the customer can operate his installation without going near the high-voltage apparatus. Neither is the meter reader in any danger of coming in contact with high-voltage wires, when making his monthly calls.

When the customer builds his own transformer vault, which is usually of brick or terra cotta construction, it is often possible to have him build in the wall a slate slab to allow of the mounting of the switches and watt-hour meters in a manner similar to that shown in Fig. 2. The back of the slab should be mounted flush with the inside of the wall. Where the slab is mounted in a 13-in. (33-cm.) brick partition, the switch handles and instruments are well protected by the surrounding walls.

Location of Transformers. The following points should be observed in selecting a location for the transformers:

1. Position of customer's load.
2. Location of operating company's street mains.
3. Accessibility for delivering material.
4. Accessibility for operating company's employes.
5. Possibilities of ventilation and sewer connection.

In the selection of a location from the electrical viewpoint, the transformers should be installed as near as possible to the center of the customer's load, as this will give him the least investment in copper and the best regulation to his various tablet boards. The company's street mains should also be considered. It is very desirable, since the connection is usually made with underground cable, to have as short and straight a run for the cable as is possible.

The location of the transformer vault should be such that the material can be delivered with as little work inside the customer's building as is possible. It should also be such that the company's employes can have access at any hour of the day or night, in case of trouble on the system. Delays caused by inability to find watchmen or building superintendents are often

FIG. 2 [FULLERTON]

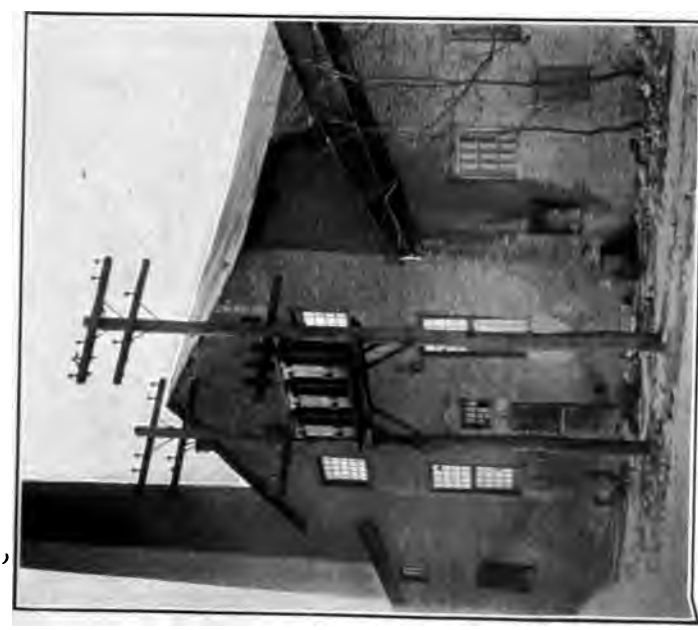

FIG. 1 [FULLERTON]

FIG. 4 [FULLERTON]

FIG. 3 [FULLERTON]

quite serious. Since ventilation and sewer connections are required, it is necessary that this be taken into account in determining the vault location and a position should be selected that will lend itself to these requirements.

Comparison of Outdoor and Indoor Installations. Some of the advantages of the outdoor installations are:

1. Less cost for making installation.
2. Usually more accessible for company's employes in case of trouble.
3. Less difficulty in connection to company's lines.
4. No transformer vault required.
5. Better ventilation.

Some of the advantages of indoor installations are:

1. Apparatus more accessible for inspection or repairs.
2. Less danger of unauthorized persons interfering with apparatus.
3. Customer can have control of the installation on the primary side, by means of oil switches, if desirable.
4. Apparatus protected from weather.

Customers' Substations Fed from Transmission System

When the demand of the customer is so great that he cannot be fed from the regular distribution system, it becomes necessary to install on his premises a substation to serve him from the transmission system, which may be of any voltage from 5000 up. Where space can be secured on the customer's property, it is often possible to supply him with service from an outdoor substation, installing switches, lightning arresters, fuses, etc., on poles and locating the transformers on a platform, on the ground, or on a suitable structural iron tower some feet above the ground.

Fig. 3 shows a 200-kw. outdoor installation in which the transformer is installed on a concrete foundation between two poles, on which are mounted the pole top switches, fuses, lightning arresters, etc., and around which is built a high picket fence with a couple of strands of barbed wire above the top of the pickets. Entrance is gained to the enclosure through a gate, which is kept locked. This is about as inexpensive an installation as it is possible to make and yet it has very satisfactorily furnished service to this brickyard for several years. The picket fence and barbed wires are even a better protection to the installation than mounting off the ground on towers,

as shown in Fig. 4. Boys are not so apt to climb the picket fence as they are to climb the towers.

Fig. 4 shows an installation in which the transformers are mounted some ten or twelve feet above the ground on a structural steel construction, the top of the tower, like the poles in the previous case, being used for mounting the switching apparatus. This makes a very good arrangement up to the point where the transformers become too large to be handled readily.

Where it is not possible to secure outdoor space or when objection is made to the outdoor installation, the apparatus must be installed in a building either erected for the particular purpose or in one that is already constructed and can be used for the installation. Where the power is to be supplied to machines in a large factory, it is often desirable to enclose a small space for substation purposes in the building near the center of the load.

Fig. 5 shows the inside view of a substation erected in the center of a large screw and bolt works. The building is of steel and corrugated iron construction. The high-tension service is brought to the substation through cables supported from the roof of the building. By this arrangement, the substation was located near the center of the load and not only saved the customer considerable on his copper investment, but gave him good regulation to his motors, which would have been impossible with the substation located at one end of the factory, at a point which he had selected and at which point he was very determined the installation should be made. This customer is served with two high-tension lines, his running load being approximately 1000 kw. Three 375-kw., single-phase transformers controlled by automatic oil circuit breakers are used. The transformers are connected to the bus on both the high- and low-tension sides by disconnecting switches, thus enabling any one transformer to be cut out for either inspection or repairs without interrupting service. The customer's switchboard and motor-generator set are located in one end of the substation building.

In another case, where a substation was built in the center of a large steel mill, it so happened that the works were built on either side of a street, so it was possible to locate the substation in a very accessible point and still keep to the center of load. The substation was designed so that it would be able

to handle the entire power requirements of the mill. When the installation was first made the demand was only about 400 kw., but they have been steadily increasing their demand until they now have connected about 2500 horse power and are making inquiries for more. Hence is emphasized the necessity for designing substations so that additions can be made from time to time as the customer's demand increases.

It is usually quite difficult to make the customer see that he should allow ample space in his substation, so that increase in size of apparatus can be made as his demand requires. Usually he thinks that his demand will be small and that you are requiring him to give up space much too large for your purposes.

Where the customer's demand is of any considerable size it has been found quite desirable to install check meters on his service, the average of the two meters being taken as his consumption. When there is a difference of about 2 per cent in their readings, the meters are recalibrated.

The following points should be observed in selecting locations for and in designing customers' substations:

1. The installation should be as near as possible to the center of the customer's load.

2. The installation should be at a point where it will be least in the customer's way, and still be accessible to the operating company.

3. If outdoors, the installation should be well enclosed, so as to prevent unauthorized persons from getting into danger.

4. The design should be such that additions and repairs can be made to the equipment with the least possible interruption to the customer's service.

5. The design of the building should be such as to allow of the ready changing of transformers as demand requires.

6. The source of power should be such as to give him the most reliable conditions of service. Customers who are vitally effected by outages should be furnished with emergency service.

7. Apparatus should be so arranged that the customer can handle his own switching at the direction of the operating company.

8. Installation should be made as well insulated and as nearly fool-proof as possible, since it is usually operated by men unfamiliar with high-tension current.

Comparison of Outdoor and Indoor Installations. In customers' substations the field for the outdoor installations seems to be with the smaller isolated customer, where he has vacant space about his plant. Where the larger installations are made, the outdoor type does not seem so well adapted.

Some of the advantages of outdoor installations are:

1. No cost for new buildings.
2. No space required in customer's present buildings.
3. All high-tension current kept outside of customer's buildings.

Some of the advantages of indoor installations are:

1. More reliable switching equipment can be installed.
2. Better facilities for inspection and repair.
3. Apparatus protected from weather.
4. Switching can be handled more easily by customer.
5. Less danger of accident to public.
6. Safer arrangement of apparatus possible.

Company's Substations

Where the operating company generates its power at a large central station, which is usually at a point quite remote from the demand, or where it purchases power from some transmission company, it is necessary for it to receive current at a much higher voltage than that at which it can distribute to the small light and power consumers, hence, it is obliged to install a substation to transform the power from the transmission voltage to a lower distributing voltage. The size of this substation, of course, depends upon the character of the district to be served, which may be anything from a small suburban town, having a small demand, to the thickly populated power district having several thousand kilowatts demand.

When it has been decided that the time is ripe for a substation in a certain district, one of the most important and by no means the easiest problem is the selection of a location. Some of the points which should be considered in making a selection are:

1. Location of the present load.
2. Future development of the district.
3. Distance from existing substations on the system.
4. Outlet from the substation for the various feeders.
5. Street frontage.

The above points determine the geographical location for the substation in the district. It is not always best to locate

FIG. 6 [FULLERTON]

FIG. 5 [FULLERTON]

FIG. 8 [FULLERTON]

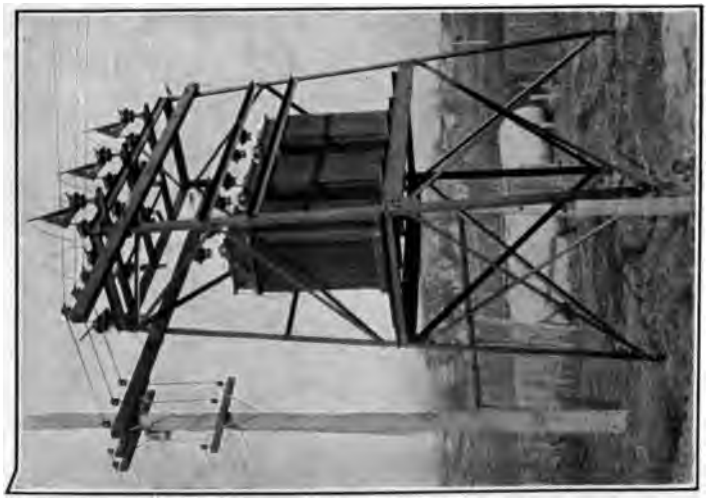

FIG. 7 [FULLERTON]

in the center of the existing load, as the tendency may be toward development in one particular direction due to natural conditions in this section. Again, the demand may be too close to an existing substation to warrant a second one, therefore, it may be advisable to locate to one side of the present load, and be in a better position to handle the growth outward from the present substations.

The outlet from the substation should be given considerable attention; if aerial lines are to be installed, a location such that it is possible to feed in at least two directions should be selected, and a corner lot would be preferable, where the lines could radiate from the substation in four directions. This means that the pole line from the substation will not be so heavily loaded as if only one outlet were available. Even though it be an underground district, it is quite desirable to have several outlets and save congestion in subways.

Substation Buildings.—Probably one of the least expensive buildings suitable for substation purposes is that made of structural steel and corrugated iron, but while this building is comparatively low in cost, its life is also comparatively short, and on the whole it is not very desirable.

A type of building, which compares very favorably in cost with one of steel and corrugated iron, but which has much greater life, is shown in Fig. 6. This building is simply an enlargement of the slab transformer vault construction referred to earlier in this paper. It is built up of structural steel on which are bolted two-in. (5-cm.) reinforced concrete slabs of standard size; the roof is also made of these slabs, supported by the framework of the building. The concrete roof is covered by a tar paper and gravel roofing. About a six-in. (15.2 cm.) slope to the 12-ft. (3.6 m.) width is allowed. Steel sash, wire-glass windows and steel louvres are used. For air supply, a section of concrete is left off one or two of the lower slabs, leaving the expanded metal reinforcing exposed. This allows a free inlet of air and at the same time prevents large objects from entering. Regular 1½-in. (3.8 cm.) expanded metal is used in the construction of the slabs.

This building compares very favorably in appearance with that of the average garage or out-building which may be found on back streets or alleys, and makes a fireproof construction. It is also portable and can be used to good advantage at a location from which its removal at some future time may be

desired. This building is 12 by 18 ft. (3.6 by 5.4 m.) and 15 ft. (4.5 m.) high. In it are installed three 250-kw. transformers serving four 2200-volt feeders.

Where a better type of building is required, brick or stone is usually used in the construction and as elaborate a design as is desired can be utilized. By the use of rock faced brick and sawed stone, a building very pleasing in appearance can be constructed at a reasonable cost.

The cost of buildings, or their equivalents, for substation purposes varies so widely, due to location and cost of labor, that it is impossible to give an estimate that would meet all conditions; however, I am giving a relative value to the various types, taking as a unit the least expensive installation—that with the outdoor apparatus installed on a concrete platform and enclosed by a fence.

Concrete foundations, poles, picket fence	(Fig. 3.)	1.00
Structural steel tower	(Fig. 4.)	2.25
Steel and corrugated iron building	(12 by 18 ft)	4.50
Steel and concrete slab building	" " "	6.75
Ordinary red brick building	" " "	15.00
Rock faced brick and sawed stone	" " "	25.00

Substation Installations. Like the buildings, the electrical installation has a very wide range of possible combinations. The outdoor substation is the cheapest, especially where no switching or regulating apparatus is required. However, it does not seem particularly well suited for installations where there is small apparatus such as instruments, oil switches, feeder regulators, etc., which should be housed. Of course, it would be possible to put the transformers and high-tension apparatus on the outside, erecting a building for the housing of the low-tension apparatus. Installations of this type have been made and work out very nicely for the small demands, but the present designs for outdoor switching apparatus for 10,000 and 20,000 volts are not such as to allow of very large installations being made along these lines.

It frequently happens that a transmission line may pass by a small hamlet or power customer from which a small revenue can be procured and still the income will not justify making a very expensive substation installation. This class of business can be taken care of by an outdoor substation. By an installation of this kind the town is furnished with electric light, which it may very much desire, and the operating company receives a small revenue from a district which would not allow

of the installation of a regular substation building and apparatus. Fig. 7 shows an installation of this type. The transformers are mounted on a tower construction some feet above the ground. Pole top switches, fuses, etc., are used, no regulators or switches being installed on the low-tension side. If regulators are necessary, the outdoor pole type can be used.

Diagram *A*, Fig. 15, shows the wiring of this installation. The apparatus is connected to the transmission line through a switch and fuse, a choke coil and ground horn being inserted between the switch and fuse.

Diagram *C* shows the wiring of the installation made in the concrete slab building shown in Fig. 6. The transformers are protected by high-tension fused circuit breakers which also act as disconnecting switches for the incoming transmission lines, the transformers being connected directly to the high-tension bus. On the low-tension side each circuit is controlled by an oil switch and fuse. Lightning arresters are mounted on the poles outside the building.

Neither of the above installations can really be said to have a high-tension switchboard. This is scarcely necessary where the substation is small and is fed by only one or two transmission lines. Where the substation is important enough to have feeders from separate power houses, or where it is used as a switching station for high-tension lines, it is necessary to install some type of high-tension switchboard.

The simplest and probably the cheapest installation that can really be called a switchboard is the open wire type. Fig. 8 shows a fair example of this type of construction. The oil switches are mounted in concrete cells, while the busbars, disconnecting switches, etc., are mounted on framework above the switch structure. The spacings of the wires are kept at 12 in. (30.4 cm.) or better for opposite polarities. Cambric-insulated flameproof wire is used throughout. Disconnecting switches are installed on both the high-tension and low-tension sides of the transformers, so that one transformer can be disconnected without interfering with the service. Where open wiring is used, it is always painted a standard color, such as red for 11,000 volts, drab for 2200 volts and white for 110 volts, and this arrangement of colors is adhered to throughout the system.

Diagram *B*, Fig. 15, shows the wiring of a layout of this type. Both incoming and outgoing lines feed through oil circuit

breakers to the high-tension bus. Disconnecting switches are always installed on each side of the oil breakers.

Fig. 9 shows, in section, the arrangement for a double-bus open wire construction. The double bus arrangement is necessary where different combinations of high-tension lines are desired. This installation is very compact, yet all wires have ample clearance for both safety and ease of construction and repairs.

The next step toward safety is the use of the cell structure.

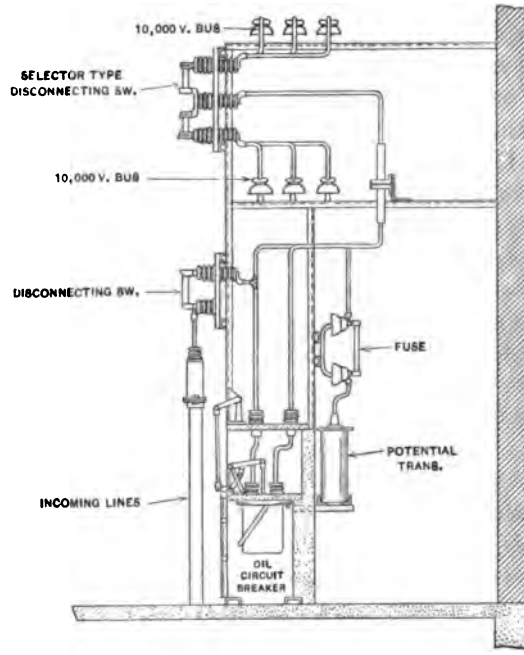

Fig. 9

In this arrangement all wires are separated by barriers of some description; soapstone, slate, concrete, ebony wood are some of the materials generally used. I will touch only on the use of concrete. This is probably the cheapest and gives a grounded surface for mounting the equipment, thus depending entirely upon the insulation of the apparatus.

When the cell structure is referred to, we usually think of something quite massive, but it is sometimes desirable to erect a cell structure and at the same time economize floor space.

Fig. 10 shows, in section, a double bus installation in which the busbars, series transformers, fuses and most of the disconnecting switches are mounted in compartments. The roof trusses are built through the cell structure, so that most of the available space is utilized. The lines enter through roof tubes between the vertical cell barriers. Connections to and from the oil switches are made with cambric-insulated wire

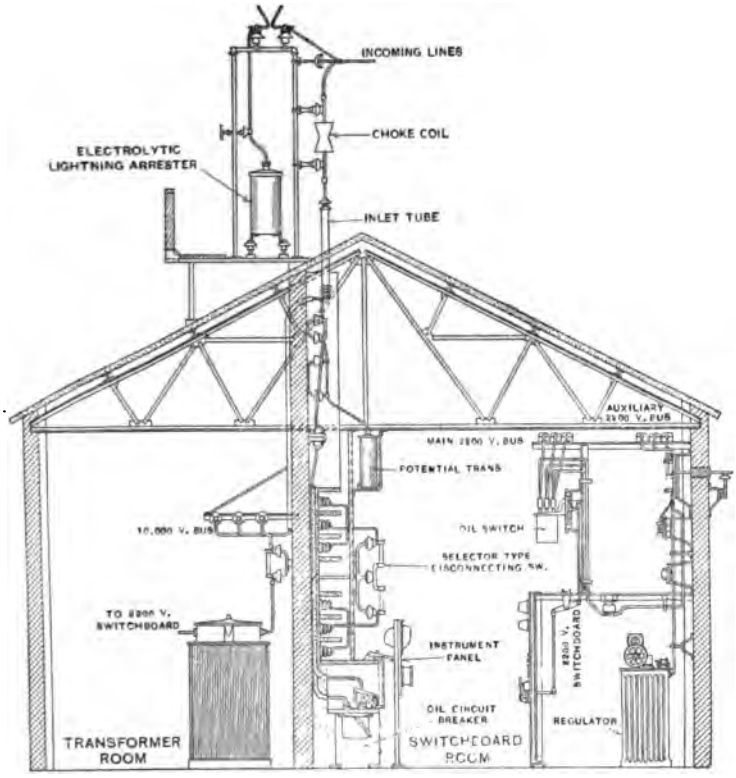

FIG. 10

in fiber conduit mounted in the concrete wall. To the right in the figure, the 2200-volt feeder switchboard, built in a double deck arrangement, is shown.

On the roof of the station are the outdoor electrolytic lightning arresters. A ladder is provided at the end of the building for use in getting to the roof to operate the arrester equipment.

Diagram *D*, Fig. 15, shows the wiring of this station. The

lines feed in through oil switches to selector type disconnecting switches, and thence to each of the buses. One bus is sectionalized so that some of the lines ordinarily feed through to other substations entirely independent of the load in this station.

Figure 11 shows the inside view of this station, with the high-tension concrete structure to the left and the 2200-volt incandescent feeder switchboard to the right. In the construction of this feeder switchboard, remote-control oil switches were used, which means all 2200-volt apparatus was kept away from the switchboard panels. Automatic voltage regulators were used on each feeder.

A more elaborate concrete structure is that shown in Figs. 12 and 13. Fig. 12 shows the front view of the concrete structure and Fig. 13 the section of a double bus switchboard. All circuits are connected to each bus through remote-control oil circuit breakers. The insulators supporting the bus also make connection between the bus and the connections to the disconnecting switches. The switchboard panel is directly in front of each high-tension panel, thus allowing the use of hand-operated oil circuit breakers.

In the structure, notice the location of the oil switch at the bottom. This is made possible by the use of single-conductor lead cable clamped to the concrete and connecting the upper disconnecting switch with the oil circuit breaker. The horizontal barriers between buses are hung from the center web of the structure without any supporting posts at the outer edge. This allows of ready access to the buses. Space was also particularly valuable in this case, as is indicated by the position of the roof truss. Provision is made for adding larger switches in series with the present ones on the main floor at some future time. This switchboard serves not only for substation purposes, but is a distribution board for high-tension circuits to other substations.

Diagram *E*, Fig. 15, shows the wiring of this switchboard. All circuits are double-throw on either bus. The buses are sectionalized by disconnecting switches to allow of greater flexibility in switching. The transmission lines can be operated in multiple or separately, each one feeding its own section of load. By operating separately, trouble on one section will not generally affect the other parts of the system.

FIG. 11 [FULLERTON]

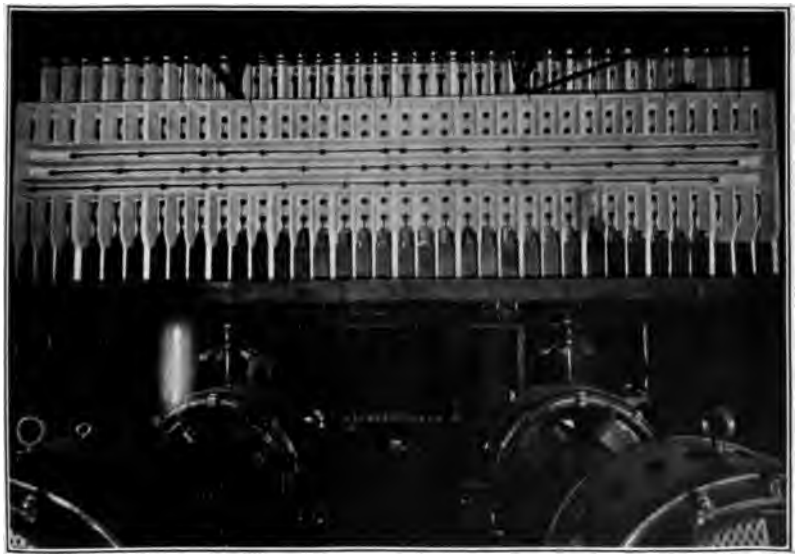

FIG. 12 [FULLERTON]

FIG. 14 [FULLERTON]

I cannot pass the subject of concrete cell structure without a few words regarding the method of construction. The usual method of building these cell structures is by erecting forms and pouring the concrete, using reinforcing rods where necessary. Owing to the difficulty of securing a uniform and smooth

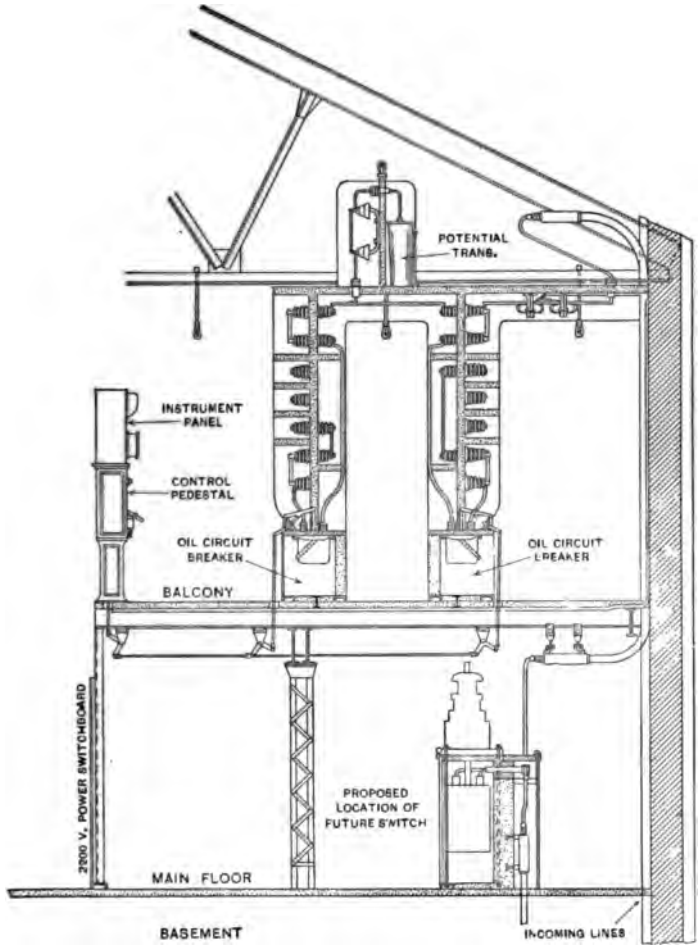

FIG. 13

job, we have digressed a little from the usual method and are building an expanded metal framework and plastering the concrete body onto it. The thickest portions plastered are three inches. The scratch coat contains a small quantity of hair, the remaining coats being pure cement and sand. The finishing

coat is of Keen cement, which gives a hard, white, smooth surface. In the finishing coat, a small quantity of lime is used to make the cement work more smooth.

Figure 14 gives an idea of the method of constructing the expanded metal framework. Angles are used in the heavy barriers and small channels are riveted or tied to these, the

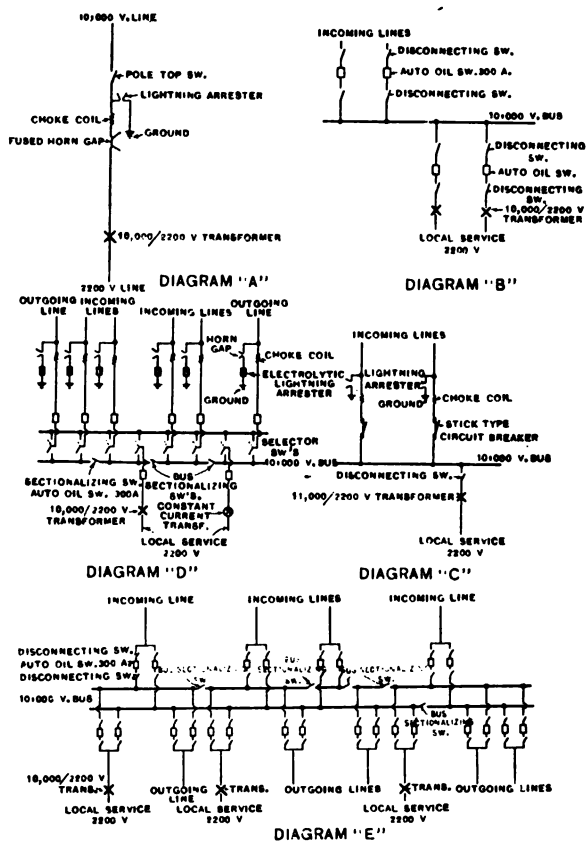

FIG. 15

expanded metal being wired to this skeleton framework. Where the structure is built as in Fig. 11, the reinforcing is keyed into the main wall.

COMPARISON OF OUTDOOR AND INDOOR INSTALLATIONS

In company substations, the field for the outdoor installation seems to be with the small towns which can be picked up

along the route of the transmission system without considerable line extension. Where larger municipalities are handled, it is usually desirable to install emergency service which requires more or less high-tension switching, and an indoor substation is usually desirable.

Some of the advantages of an outdoor installation are:

1. Little or no cost for building.
2. Less cost for high-tension apparatus.

Some of the advantages of an indoor installation are:

1. All apparatus protected from weather.
2. Greater ease of inspection and repair.
3. Less depreciation on equipment.
4. Less danger of accident to inquisitive persons.
5. More reliable high-tension apparatus procurable.
6. Safer high-tension construction possible.

Presented at the 2d Midwinter Convention of the American Institute of Electrical Engineers, New York, February 25, 1914, under the auspices of the Electric Power Committee.

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OUTDOOR SUBSTATIONS IN THE MIDDLE WEST

BY LESLIE L. PERRY

ABSTRACT OF PAPER

Conditions in the Middle West, particularly in the agricultural districts, have often been such as to necessitate the construction of small 33,000-volt outdoor substations in order to make the supply of current commercially practicable.

These stations have been constructed with very simple switching and protective equipment, and economy of design and protection to the main line have been the dominating feature of design.

Operation of such stations has been successful and they are of great benefit to the communities served.

Improvement in lighting and overload protection is looked for.

THE CONDITIONS in such states of the Middle West as Illinois, Indiana, and Kentucky, are very favorable to the use of small outdoor substations. Many of these have been built during the last year, and more undoubtedly will be built in the next few years. There is little very high-tension transmission within 300 miles (482.8 km.) of Chicago, but there is a large amount of 22,000-volt, 33,000-volt, and some 50,000-volt transmission. These lines for the most part serve districts that are not densely populated. In many sections, particularly in Illinois, the communities are almost purely agricultural, with only those small industries associated directly with agriculture.

In the manufacturing States, particularly in New England, oftentimes a factory or mill can readily supply electricity made either by water power or steam on a moderate investment cost and with a very low operating expense. But many of the richest agricultural districts of the Middle West are without small reliable water powers, and cheap, economical steam plants are impossible under the conditions.

Many towns of 2000 people have three-fourths of their people within a radius of a mile (1.6 km), and the entire electrical business of one of these towns may not warrant the expense of more than a single man devoting his entire attention to electric service. Where, as occasionally, local plants have

been built, they usually have rendered very indifferent service, and seldom operate throughout the 24 hours. With a distribution system of 33,000 volts nearby, of course continuous service can be readily given; but in order to make such service commercially possible, investment and operating costs must be kept within the lowest reasonable limits.

It frequently happens that such local plants as exist have not enough floor space or headroom to house 33,000-volt apparatus, and in other cases there are no suitable buildings, so that immediately there comes up the question of building investment.

In the climate of Chicago, it is the opinion of many engineers that somewhat more reliable operation will be had with indoor apparatus, and where housing has to be provided for considerable apparatus, such as street lighting equipment, feeder-regulators, and perhaps a motor-generator or a synchronous converter, the size of the load and the number of customers served warrants a new building. Of course, with voltages of 60,000 and above, the indoor station would not be possible where it can be used at 33,000. Where the load is below 300 kw. it is often considered that on voltages of 33,000 and above, the cost of any high-tension oil switch and aluminum cell arrester is not warranted, so that very simple outdoor high-tension switching and protective gear with the outdoor type transformers make a substation equipment well adapted to the requirements. Where no indoor space is available, just enough housing is provided to protect a low-tension oil switch, a watt-hour-meter, ammeter, and voltmeter, with space for a street lighting regulator if required.

While many stations have supporting frames built of wood, undoubtedly more and more of them will be built of steel. At first thought one would consider the wood much cheaper; but taking into account that the steel structure can be built by efficient shop labor with minimum erecting costs, while the wood structure requires the less efficient field labor, and does not have the reliability, life, or freedom from fire risk that the steel does, it will be found the wood structure is not any cheaper.

A station to handle three 50-kw. transformers can be supported on a tower with a six-foot (1.8-m.) base as shown in Fig.1. A six-foot square house of galvanized iron or heavy sheet steel is ample for most requirements and accommodates a 2300-volt low-tension panel as shown in Fig. 2, and incandescent outfit for street lighting.

[PERRY]

FIG. 1—33,000-VOLT OUTDOOR SUBSTATION EQUIPPED WITH TWO 50-KW. TRANSFORMERS AND SPACE FOR THIRD.

[PERRY]

FIG. 2—LOW-TENSION PANEL USED WITH OUTDOOR SUBSTATIONS.

These substations are connected to transmission lines supplying substations of larger size, say 600 kw. per station and above; provision should therefore be made to automatically cut free these outdoor substations from the transmission lines in case trouble develops in the small station. Hence, in the supply of power to the small rural station, the chief requisites to be met are: 1, economy of design, 2, protection to the main line, and 3, reliability of service in so far as the elements of the outdoor station itself are concerned.

Up to the present these stations have been very successful. The problems of overload and lightning protection have been solved with reasonable success, but unquestionably improvement can be made in these directions. In the absence of better devices of reasonable cost, either the plain wire fuses on horn gaps, or the liquid high-tension fuses with or without horn gaps, have been chiefly used for protecting the line, reliance being placed on the low-tension devices for overload on the substation itself.

For lightning protection a ground gap has been used, and the substation fuse is so mounted as to protect the line when the line current too freely follows the lightning. Choke coils are used in the transformer leads.

In designing such stations it should be remembered that they will often be in the hands of inexperienced operators, and hence every precaution should be taken to permit proper attention by ordinary emergency men; for this reason many stations have been built with disconnecting switches on a separate pole with lever gear such that the switch can be operated by any intelligent man. With this arrangement fuses can be replaced or defective transformers exchanged on a structure absolutely without any live wires connected to it.

In mounting the transformers well above ground, due regard has been paid to keeping the high-tension apparatus as free as possible from interference by careless or inquisitive boys, marauding animals, or the washerwoman's wind-blown laundry.

Sufficient success has been attained to demonstrate that by using these small outdoor stations good electric service can be supplied rural communities at attractive prices, and the central stations and the manufacturers are rendering true public service in reaching communities otherwise unable to benefit by central station service.

DISCUSSION ON "OUTDOOR VS. INDOOR SUBSTATIONS" (MACOMBER), "OUTDOOR SUBSTATIONS IN NEW ENGLAND" (HUNT), "INDOOR AND OUTDOOR SUBSTATIONS IN PENNSYLVANIA" (FULLERTON) AND "OUTDOOR SUBSTATIONS IN THE MIDDLE WEST" (PERRY). NEW YORK, FEBRUARY 25, 1914.

A. H. Kruesi: The time has passed for the discussion of the design of outdoor stations, and we must get down to the results of experience. The difference in cost generally between an indoor and an outdoor substation, taking buildings, equipment and steel structures, wiring, installation; etc., all into account, is generally not very large.

Mr. Hunt states that for the case he describes the difference is only about 11 per cent. That, I think, means that the outdoor substation should be restricted to comparatively small installations, like those, for example, which serve a single factory or industry. I think that for a substation which might cost anywhere from $20,000 to $50,000, a saving of $2000 to $5000 is altogether trifling, compared with the continuity of service which a city has the right to demand of a public service company, and that for such a small saving one would not be warranted in going to the outdoor construction if it can be shown that the risk of interruption due to the outdoor location of the apparatus is materially greater.

Two of these papers show photographs of outdoor stations for industrial plants using steel towers with the transformers placed on platforms on the towers. That makes the towers more expensive, due to the dead load, and the wind load, and I wonder if the transformers are put upon the platform as a matter of habit, because we have been hanging transformers on poles, or whether any real good is accomplished by having them up in the air. It costs more money, and in an emergency such as a burnout of a transformer it will require more time and money to take the defective transformer down and put a new one in its place.

A. R. Smith: The outdoor station is now some years old, and there are many of various capacities in existence, apparently giving satisfaction. The relative merits of the two types have frequently been discussed in a general way. What we want now are some records of actual operating troubles in different climates.

The reason for the existence of the outdoor station is economy, and there is no doubt that in many cases economy has resulted from the adoption of the outdoor station. There is, likewise, no doubt that many have been deceived in believing that they economized in resorting to the outdoor design.

The writer believes that there is a field for outdoor stations, and that the small transformer station of any potential without oil switches or attendants, and the large transformer or switching station of 60,000 volts and above, represent the two classes where economy in first cost can be shown. However, the saving in the

latter is largely a matter of the system of connections adopted.

There are many considerations as regards the choice between the indoor and outdoor station which have not been generally discussed and which the writer would like to suggest, with the hope that further data will be forthcoming. In fact, engineers in general are uncertain as to which policy should be pursued, and more enlightenment on the subject will enable us to proceed along definite lines with much greater assurance.

Oil-cooled transformers. The capacity of an oil-cooled transformer is wholly dependent on the area of radiating surface and the rate of heat transmission per unit of surface. The temperature of the transformer case when exposed to the sun may be from 15 to 20 deg. fahr. hotter than if protected from the sun's rays. If the temperature of the oil is 135 deg. fahr. and that of the case is 115 deg. fahr., the difference of 20 deg. gives the factor of heat transmission. Now, if the case were shaded, the difference would be from 35 to 40 deg., which means that the outdoor transformer has to be much larger.

It has been suggested that the transformer tanks be painted a light color to retard the heat absorption, and this should be effective; but the radiation of heat from the tank to the air is something like a ratio of 14 to 19 for light and dark colored surfaces, so that the net gain is a question.

The radiation is also directly affected by the velocity of air due to the convection currents caused by the heat emitted from the transformer. In the case of an outdoor transformer the height of the chimney effect is approximately the height of the transformer, as the heated air is immediately diffused after leaving the top of the transformer. On the other hand, the ventilation of an indoor transformer can be directed and controlled so that a uniform circulation on all sides is maintained and a chimney effect of two or three times the height of the transformer obtained. It may be argued that the relative costs of the two types of stations have been based on the manufacturer's costs of the two types of transformers; but the manufacturer has been obliged to use a factor of safety on indoor transformers much too high because so many transformers have been placed in buildings without any consideration for ventilation. Now, give the manufacturer a drawing showing a perfectly ventilated building for the transformer and then compare the costs of the indoor transformer with the outdoor transformer having more radiating surface or smaller copper and core losses; outdoor bushings; water-tight covers; non-freezing oil, or the capitalization of the losses due to exciting idle transformers; heating coils, and the capitalization of losses in the same, and we will find a greater difference than anticipated.

Water-cooled transformers. Water-cooled transformers are better suited for outdoor service, but these too have objectionable features. First, the water has to be kept in circulation in all idle transformers every day that the temperature is below 32 deg. fahr., which entails a pumping expense, and extra valves and

drains are necessary so that no water is left standing in dead-end pipes when a transformer is removed in cold weather. Second, oil-drain piping has to be designed without pockets which might become filled with moisture of condensation and freeze, and all valves have to be kept in working order. Third, the circulation of water in an idle transformer has a tendency to keep the oil from freezing, but it might be necessary to arrange to use the warm water obtained from the transformers in operation and then, at the best, this is very ineffective as the water coils are at the top of the transformer and all heat transmitted to the oil at the bottom is by conduction and not by convection.

In general, the heat produced by the transformers is wasted in winter when it is most needed, and in summer, when it is difficult to dispose of the heat, the transformers are located in the warmest place—in the sun.

Lightning arresters. With an efficient electrolyte the film dissolution on the cones is very rapid when the temperature exceeds 100 deg. fahr. To insulate the arrester tanks from the sun's rays is objectionable because it confines the heat if the arrester is discharging frequently. It has therefore occasionally been necessary to protect the arrester by means of a sunshade.

Oil switches. During rainy weather short-circuits are most prevalent, and it is often advisable to inspect the oil switch contacts after rupturing a severe short-circuit. In the case of the outdoor oil switch, this can only be done in wet weather by removing the switch to the repair shed, because of the possibility of permitting moisture to enter the tanks.

It has long been acknowledged in the design of steam plants that apparatus located in hot, wet or inaccessible places does not get the attention from the operator that it should. Now, how much attention is going to be given to the oil switch operating mechanism during stormy weather? Will not repairs and inspection be postponed for more favorable weather? What is the possibility of the switch failing to open due to this lack of attention and postponement of repairs? What is the life of a switch and consequent depreciation of an outdoor switch as compared with an indoor switch, and what does it cost to provide facilities for transporting the oil switch to the repair shop upon the least provocation?

In some outdoor installations it has been necessary to provide by-pass disconnecting switches so that the switch could be left in disuse until a favorable opportunity presented itself for repairs.

High-tension wiring. Buses and disconnecting switches are the safest to locate out of doors, and they really require the most building space. A semi-outdoor station is possible and economical with certain wiring connections, where the apparatus is protected by a moderate size building, and all of the wiring located out of doors.

Fire risk. It is frequently claimed that the outdoor station is a better fire risk than the indoor station; but this may or may

not be true. The spacing between conductors out of doors may be considerably greater, but at least 50 per cent greater spacing is necessary to obtain the same factor of safety, because of the rain and the wind which will start an arc sooner and carry it farther. Then there is the transformer fire risk. We can readily imagine the resulting damage if a transformer should get on fire adjacent to a steel tower, the failure of which might result in the collapse of the entire steel structure of bridges so often employed.

Facility of making additions. The outdoor station can readily be added to or changed; but it cannot be readily housed in if the outdoor scheme is found unsuited for the climatic conditions. Furthermore, if all of the money is invested in the apparatus, the cost of replacing it due to obsolescence, inadequacy or depreciation is proportionally increased. The life of a building is usually considered to be at least twice that of the apparatus.

General considerations. The maintenance of the outdoor station structures should not be materially different from the building structure, as the steel towers should be painted, provided the wiring is arranged to make painting possible, and the walks, foundations, fences, repair shop, and operating house kept in repair. The cost of maintenance of the outside apparatus will probably be more than the inside apparatus.

In cold climates there are the snowfalls and drifts to contend with, which means extensive shoveling of paths, and the clearing of the tracks and turn-tables of ice. And during electrical storms, all of the apparatus is exposed to a direct stroke of lightning, as choke coils cannot conveniently be arranged always to direct the lightning to the arresters.

These objections are set forth, not with a view to discourage the use of outdoor stations, but to show that the saving of a $25,000 or $50,000 building does not necessarily represent the net saving, and that the resulting saving is not always sufficient to warrant the adoption of the outdoor station, if reliability is to be sacrificed or maintenance increased.

Roy E. Argersinger: We must see a very large saving in order to make the outdoor substation worth while, as I believe the danger we run into ought to be very seriously considered. For instance, if we get a bad storm, we are more likely to get trouble at that time than when the sun is shining, and we do not want to go out and pull the transformer apart when a heavy storm is raging. It is hard to get any one to work on the outdoor substations during such conditions. During the last week in our country we have had the thermometer down to 15 and 18 deg. below zero, and it is hard to get linemen to look at the line, to say nothing of the station, under such conditions.

H. B. Gear: It seems to me that the economic question whether or not the outdoor substation pays is very largely a question of determining the balance between the cost of the building and the cost of the rest of the equipment. In industrial substations running from 150 kw. to 1000 kw., the possibility of an outside

substation is just as likely to be fixed by local conditions as by the desirability of saving the cost of a building. In some manufacturing plants there is no available space for the placing of a substation. The equipment must be placed on poles in the public thoroughfare or installed in a vault, if the line is underground.

For the smaller substations it is not entirely an economic question. The cost of the building, if a separate building is erected for the purpose, is apt to be as much or more than the cost of the equipment itself in the smaller sizes, and therefore anything in the way of an enclosing building becomes a considerable addition to the total investment.

As we pass up to the higher capacities, and where the outdoor installation becomes desirable, because of the fact that the service is supplied by very high voltages, the problem becomes a little different. The tremendous separation required for 66,000 volts, naturally suggests putting the apparatus outdoors rather than building a structure big enough to provide necessary clearances. In the case shown in one of the papers, the saving figured out is about 11 per cent. At lower voltages, and with large substations such as are found in metropolitan work, with several thousand kilowatts involved, the amount which may be saved is a much smaller percentage, since the potential regulators, the switchboard equipment and all the accessories required in distributing from a substation, as a matter of giving good service, must be placed indoors, and only the transformers and the switching equipment could go outdoors. In this class of installation, it will not often be found that a great deal can be saved by building an outdoor substation for the transformer equipment.

The point which is touched on in Mr. Perry's paper with regard to the use of outdoor substations in high-tension distribution is an important one. The ability to serve large areas by means of 33,000 volts, as is being done in Northern Illinois, is dependent largely upon the possibility of locating comparatively small substation equipment out of doors. There are numerous cases where transformers as small as 50 kw. are supplying towns along the route of the line in which it is possible to give fairly good service without anything but a platform and a little local construction. This would not be possible from an economic point of view, if it was necessary to construct a building and use the type of equipment which was considered necessary for a substation a decade ago. Outdoor construction may be applied in a variety of ways and has a very definite place in electric distribution.

W. S. Moody: The four papers that have been presented on outdoor transformer stations give a very good general review of a recent development in our art. It is not a radical improvement in the sense that it requires any great change in previous methods of designing apparatus, or any inventive ability on the part of the manufacturer, and yet, it does mark an important epoch

in electrical developments, which, I believe, will be more fully appreciated as the practise becomes more general.

As has been pointed out, the innovation in practise started purely on its economic showing. Both the manufacturer and the operator shrank a little from the idea at first, because it clearly increased the risk for both, but none of the various possible sources of trouble are really inherent and it only needed, therefore, some experience and a close and intelligent study of details to avoid them.

If I may be allowed, I will point out two respects in which the papers do not give an entirely correct idea as to how far this practise has progressed. It is stated that there is something like 300,000 kv-a. in outdoor transformers installed or contracted for. Those for whose design I am responsible alone amount to 25 per cent more than this figure, so it is fair to assume that the actual capacity of such transformers so far produced may be nearer 600,000 than 300,000.

The other incomplete impression given is as to the maximum size of units and installations. Units have already been built up to at least 7500 kv-a., and installations up to 50,000 kv-a.

The most important features to be cared for in an outdoor design (as far as our experience yet goes) are:

(a) Covers, joints around leads, man-holes, etc., must be thoroughly weather-proof. This not only means that they be rain-proof, but so completely sealed as to be water-tight when ice and snow build up and hold water over the joints.

(b) That the leads be made of such material and in such a manner as to be entirely unaffected by the weather.

(c) That the tanks be so ventilated that they will not take in rain or snow and yet may relieve themselves from moisture and gases.

(d) That idle units be heated sufficiently to avoid their being at a temperature lower than the atmosphere.

I want, in closing, to say a word of caution with reference to the needless use of outdoor installations. Some people are anxious to use the latest thing, whether it is best for their conditions or not. It should be borne in mind that however well the apparatus may be designed for outdoor service, it cannot be quite so safe or convenient when so installed as if it were protected from the weather, consequently the lower cost of installation and possibly a little less fire risk are the sole reasons for outdoor installation, yet I have seen such installations right beside large stations that had and probably always will have more than ample space for the transformers inside. In such cases considerable extra expense had to be incurred in carrying both high- and low-tension wiring, already inside of the building, out to the transformers and back. Such an installation made simply to be in style is certainly not good engineering.

Allen M. Rossman: Mr. Kruesi asked the reason for putting the transformers in various substations above the ground. With

reference to the substation shown in Mr. Perry's paper, there were two considerations which led to this design;—one was to keep the 33,000-volt wiring up out of the way; the other was to provide, within the structure, a housing for the low-tension (2300-volt) meters and switches and for an arc lighting transformer, if needed. Consequently, the whole substation is self-contained.

I might say, regarding the cost of this particular substation, that the structural steel as shown, together with the fuses, horn gaps, choke coils and disconnecting switches complete—the structural steel being galvanized—cost very little more than would a first-class 33,000-volt oil switch, and it is only by reason of this low first cost of substation that an extensive 33,000-volt distribution system supplying a large number of small scattered customers is possible.

J. C. Smith: We have had very little experience with the large outdoor type of substation around Montreal, and in other sections of Canada, probably because the use of an outdoor substation would involve the use of naturally cooled transformers. We could not use water-cooled transformers on account of the temperature conditions. For example, at our power plant, for the last four weeks the temperature has not risen above zero, so that you can imagine to take care of water-cooled transformers would be quite a difficult task. So that while we have done considerable calculating on the subject, the matter always resolves itself into the fact that it would be necessary to put in, at very considerable extra expense, means for protecting the apparatus from the cold, and we have not yet had enough confidence in the oil switches to feel that we could operate them successfully under these very severe climatic conditions.

P. W. Sothman: I think I will have to agree with Mr. Smith in his remarks on this matter, as to the reason why it was decided that Ontario was not the place for the outdoor substation. I believe we would have had to spend more money for heating up the system, than for keeping it cool. In a general way I think the matter of outdoor substations should be dealt with on its merits. I think, without any question, there is a big field for the outdoor substation. On the other hand, I think there are many places where the outdoor substation is not the one which is needed. The comparison of cost, between the outdoor and indoor substation, may play, to a certain extent, some part in the matter, but I think, from the operating standpoint, we should be very careful to draw the line between saving a few per cent and then running a risk of destroying the necessary continuity of the service which is essential above all things.

When we look over the liabilities which a public service corporation assumes, when we look at the mistakes which have been made in certain sections of the country by the saving of a few cents, and thus weakening the guarantee of a fairly good service, due to not properly protecting the system, or some part of the

system, we soon come to the conclusion that such a policy is very bad engineering. I think the motto should be, first of all, continuous service, if possible, within commercial reason. If we are guided by this consideration, and in addition give proper attention to the climatic conditions, I think that will tell us where an outdoor substation should be built and where an indoor substation should be built. I think also we will see, to a certain extent, the combination some day of the indoor-outdoor substation even in big cities.

J. Edward Kearns: A careful analysis of this subject will resolve itself into two factors: first, that representing continuity of service, and second, the question of cost, including not only first cost but maintenance and depreciation.

With respect to continuity of service, the principal point, of course, is to be careful to select apparatus best suited for local conditions and that which will eliminate, as far as may be, all possibilities of shut-down. When we come to the question of first cost, a careful comparison has been made of several outdoor substations and indoor substations, which shows that the outdoor type is about 10 per cent to 15 per cent cheaper, in sizes of 2000 to 5000 kv-a. Now, perhaps, the main reason why the cost of the indoor substation exceeded that of the outdoor substation, has been due to the type of building and other architectural features brought into the construction of the building. I personally feel quite positive that if more of our smaller indoor substations were built with a very cheap sheet metal building, we would find that the general comparison would be about equal, particularly if we keep in mind the fact that it is always desirable to have an attendant when large outdoor substations of 10,000 to 20,000 kw. are installed, and, under these latter conditions, I believe it will be found that the general result will be very much in favor of the indoor type of substation.

Another important subject that has been brought out in the discussion, in addition to these two, is the question of climatic conditions, and large installations to date indicate that less trouble may be experienced with outdoor substations in southern climates than those in the northern or cooler climates, with the result that many operating companies in the North are not installing outdoor type substations, but are considering instead a very cheaply housed substation.

K. C. Randall: The very pronounced increase in the reliability of apparatus in general, especially that which is involved in outdoor installations, has contributed immensely to the practicability of the outdoor station. Transformers and breakers have been simplified, strengthened and made more substantial and reliable, with more permanent factors of safety, so that now under nearly all conditions they can be looked upon as largely free from the need of attention.

As an economic problem, there is no doubt that good consideration is required to determine definitely the justification

of the outdoor station, or, so far as that is concerned, of the indoor station. It is also possible that fashion may have brought outdoor stations into being when the indoor station might have been better, but the same can be said of the indoor station. Probably there are few men with experience who can not recall instances where the outdoor station would have been a better proposition than the indoor station which was built.

Terminals for apparatus and station outlets are so thoroughly developed, that very little or no trouble is encountered from those of best design. These were the original stumbling blocks when the outdoor apparatus for heavy potentials was first undertaken. Terminals that will stand 300,000 volts in a 45 deg. precipitation of $\frac{1}{8}$ in. per minute are in use and are entirely practicable. Terminals for all lower voltages and current ratings have been developed with equal success.

The first 100,000-volt transmission in this country, whose transformers were built under my direction, operated without lightning arresters entirely successfully with a grounded overhead line wire extending but a few miles from the stations where the transformers were installed. This was some years ago. There is no doubt that transformers of today are equally reliable, which means that the necessity for repair is remote. The same applies to switching apparatus and therefore, in general, the outdoor equipment is not likely to demand much attention.

Five years ago this subject was presented before the Institute, and it was then suggested that the outdoor station would have a place under some conditions but that no general rule could be stated for determining when the outdoor station would be justified. The four papers presented today have shown that there have been applications for an outdoor station which have been justified, for it is not reasonable to assume that all, or even many, having made these installations have been wrong in their judgment.

It is, therefore, gratifying to me to have this confirmation of the opinion then expressed. At that time many doubted, according to their discussion, and even today the same attitude would seem to prevail in some places, although the practicability and desirability of the outdoor station have been thoroughly confirmed.

Henson E. Bussey: We have quite a large number of outdoor substations. The capacities of these outdoor substations run from 20,000 to 30,000 kw., but it has always been an open question with me as to whether or not there was not a little bit of stampeding in building outdoor substations in our climate. A great many people seem to think that the South is a particularly good climate for outdoor substations. I do not think so, for the reason that very frequently we have rainfall at the rate of as much as three to four inches an hour, and at the same time extremely high winds, and if transformer tanks and switch tanks are not absolutely tight, then undoubtedly trouble

is going to develop. As to whether or not that trouble will develop, it is a question of simply waiting to see. It has not developed so far.

It seems to me that the relative advantage of outdoor versus indoor substations for any climate lies in the question of the first cost, as has been brought out, and in the reliability of operation. The question of the first cost is something which the companies which have been building these substations can very materially assist in settling. I would like to know whether or not the outdoor substations are really cheaper, considering the same class of installation, than the indoor. I very seriously doubt it. I know of one case of a 20,000-kw. outdoor substation—five of them, in fact, which were built on the same system, where the people who had charge of the building stated that it worked out in advance very much cheaper than would have been the case had they used indoor substations. After they had been built, I found that they worked out nearly fifty per cent in excess of the estimates, and now it is a question whether or not they are cheaper. It is safe to say that they could have built the indoor substation as cheap, if not cheaper.

The character of the building is an important factor, but I am firmly convinced if we could get some data from the operating companies and the people who are constructing the buildings and substations, the point will be settled once for all.

E. A. Lof: One point that must be given considerable attention in connection with outdoor substations is the protection of the transformers, both from the extreme heat in summer and from the cold in winter. While the former can be readily obtained by providing sunshades, in certain instances very good results are obtained, as stated by one of the authors, by simply painting the tanks white.

It is, however, more difficult to provide for the cold winter temperatures, especially with water-cooled transformers. With the transformers in service there seems to be no danger of freezing, and for this reason the transformers should be connected to the circuit and thus energized even if they do not carry any load. Some sort of heating grids can also be readily provided in the bottom of the tanks. The main difficulty lies in the formation of moisture which takes place when the temperature of the transformer is allowed to fall below that of the surrounding air. This applies equally well to indoor transformers, and precautions must therefore always be taken to prevent this. Much may be accomplished either by reducing the water rate at times of cold weather, or by using the cooling water over and over again.

There are a number of other points which should be given consideration in the construction of the outdoor substation. The line wires should be securely anchored before entering the station structure, and no unnecessary strains should be permitted in the wires inside the structure. Consideration should

be given to deflections resulting from different pulls on the connections, and also to unequal settlement of supporting towers which may readily cause excessive stresses and insulator breakages, resulting in service interruptions. The spacing of all the conductors, as well as that of apparatus, should be liberal, but not excessive.

The transformers and switches should be placed on concrete foundations of a sufficient height to be clear of water, and the station should furthermore be well paved and drained around the apparatus. Transfer tracks with a truck will also be found very convenient when moving the apparatus. Cement walks should be laid on that portion of the ground where the operator is most apt to pass in his inspection trips and work about the place. The oil piping to the transformers and switches, and the water piping, if water-cooled transformers are provided, should be so arranged that connection can be made or broken for any unit without disturbing the operation of the other.

Farley Osgood: In New Jersey we have no outdoor type of substation as described in these papers. We do not get the isolated conditions in our territory, which warrant such an installation, and the service is so congested, and in New Jersey is coupled together with railway service, demanding so much continuous switching, that it is questionable if the outdoor type of substation left a good deal by itself would work with us. The New Jersey territory, generally speaking, is a well solidified field of operation, with a good many substations, not very far apart, and the demands of combined service require so much personal attendance, that it is very doubtful, except in developing the outskirts of the territory, if anything but the indoor type of station would be installed. Our problems are simple, because our voltage is 13,000.

Dugald C. Jackson: I want to express this proposition as one that runs through my mind—and I think it is pretty definitely fixed there—that in the case of large substations on which a great deal depends, reliability becomes a matter of the very greatest importance, and under these circumstances the cost of the building is so small a factor of the total investment cost for the distribution system, and converting apparatus and real estate, that the saving of 20 per cent, or even 50 per cent, of the cost of the building alone may not be a factor to be considered, and consequently large substations, especially those serving cities, should ordinarily be housed under the very best conditions of fire-proof construction.

But there is a different condition to be considered, and that condition is well illustrated in Mr. Perry's paper, also in Mr. Fullerton's paper, and to some degree in Mr. Hunt's paper. It would be again illustrated if we had a paper from the Rocky Mountain region. There one has vast areas—the Rocky Mountain region is sparsely populated, the same is true of parts of the prairies of the Central West; and it is even true, in part, of

the state of Massachusetts, which, next to Rhode Island, is on the average the most populous state in the Union per square mile, yet there is a good part of Massachusetts in which the population is very sparse—this is also true of the states of New Hampshire, Vermont and Maine. In such sparsely populated territory, there is here and there a customer who should be provided with power, or a small village which should be provided with power, where, perhaps, in the past they had a small electric lighting plant of their own, but have been seeking better service afforded on a more favorable basis.

These needs of isolated individual customers and small villages of the Far West, of the Central Western prairies, probably the South, and of New England, can be served by outdoor substations, or, perhaps, by what have been called outdoor-indoor substations. Mr. Fullerton describes the latter fully and admirably. The latter development is one which seems to me to possess great economic possibilities for electrical engineering, because it may aid in the making of another step toward putting power transmission into the same category of comprehensive usefulness and importance as transportation and the transmission of intelligence.

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PROBLEMS OF HIGH-TENSION TRANSMISSION LINES

REPORT OF SUB-COMMITTEE ON TRANSMISSION

P. W. SOTHMAN, CHAIRMAN

INTRODUCTORY

IT IS not intended that the following article shall completely cover the very broad subject of transmission of electrical energy, but only outline some of the more important problems which have to be considered when building and operating high-voltage lines. Such data as are contained herein have been supplied by the members of the sub-committee with the idea of furnishing a basis for discussion, for it is recognized that the principal value of a paper of this kind lies in the discussion which it may elicit.

Some of the topics of particular interest at this time have been treated in short special articles which are published as appendices to this report and which appear under the names of their respective writers.

RIGHT-OF-WAY

In sparsely settled countries there is generally no trouble in securing as much land as may be needed for the erection of the transmission and telephone lines, and the only point to bear in mind is the choice of route involving the least constructional difficulties, such as the crossing of mountain ranges and streams or the avoiding of locations which make patrolling and maintenance unduly expensive. If a restricted locality were known to be particularly subject to lightning storms, this would naturally be avoided, if possible.

On the other hand, in districts like the East where the land is already fully occupied and sometimes quite valuable, the right-of-way problem is often not an easy one, and the question arises as to whether it may not be advisable to obtain easements, giving the company the right to erect and maintain its lines across the lands of the owners. Tower lines may even cross fields under cultivation, causing practically no inconvenience to the farmers, who have been known in many cases even to plow and grow grain between the legs of the towers themselves. For

convenience in patrolling and the making of repairs, the route should, as far as possible, be chosen alongside of highways, regardless of whether the right-of-way is purchased outright or not. The width of right-of-way is an important consideration, as well as the minimum clearances which should be allowed above ground.

There are cases in which it may sometimes be advisable to utilize the right-of-way of an existing steam or electric railway, provided a suitable agreement can be reached between the respective parties. This arrangement has been objected to at different times by laymen because of the alleged danger to the traveling public. That this objection is groundless, we all know, and decisions have been rendered by at least one State Public Service Commission to this effect. Objection to this practise has also been made by the telegraph companies occupying the same rights-of-way, on account of the interference which may be set up in such circuits because of the proximity of the power lines. By the use of proper care these troubles may be reduced so as to become unimportant, so that this objection also is overcome.

Under this heading may also be included the constructions necessary for the crossings of railways and other circuits. There is at present no generally recognized type of crossing protection, and whatever kinds are used are usually subjects for agreement between the parties concerned. Certain protection from falling wires or cables is desirable, but we feel that the matter has been carried to extremes in many instances. If two power companies adopt elaborate and expensive means for protecting their respective circuits where crossing one another, when an ordinarily substantial construction of the lines themselves would suffice, how can they object if the telephone and telegraph companies, whose lines they have to cross, insist that an equally elaborate protection be installed for their crossings also? This shows the need for an intelligent agreement upon the subject and for a code of rules or specifications, preferably bearing the sanction of the Institute, which will be accepted by all parties. Such specifications should allow a certain latitude in the construction so as not to inflict unnecessary hardships upon small power companies operating at comparatively low voltages, or those located in unsettled districts.

Towers

The selection of the type of tower depends upon the number of circuits to be carried, line voltage, whether suspension or

pin type insulators will be used, the physical characteristics of the country through which the line will pass, and also upon the climate. It is generally agreed that the square or four-legged tower is more efficient in the use of material than the three-legged tower and the latter is seldom seen nowadays in new work. The flexible type of tower has also been used to some extent with good results, but it is necessary to place rigid towers at frequent intervals along the line to act as stays, from which the flexible towers are more or less supported by the overhead ground wires and also by the power cables when pin insulators are employed. It is too early to say what success will attend the flexible tower when used in connection with long suspension insulator strings, and until more data are available upon the subject it is advisable to proceed with caution when considering the adoption of this construction.

Where suspension insulators are employed, it has been found that it is not good practise to place two or more conductors in a vertical plane, especially where snow and ice are liable to collect upon the cables. When this load breaks away it very seldom does so uniformly and the cables are in great danger of coming into contact. This phenomenon has been quite fully treated in a recent paper. It might be added that it has been observed in the East that ice seems to collect to a greater extent at the centres of the spans than near the towers, which should be taken into consideration.

The method of calculation of tower designs should be standardized, and the constants for such materials as copper, aluminum and steel used for conductors should be taken at some acceptable figure such as 30,000 lb. for copper, and 14,000 lb. for aluminum, as representing the elastic limit of the material. The design should be calculated so that when the loads estimated are all on, the structure will be stressed to the elastic limit. The factor of safety is therefore in assuming excess loads over those which are known to be liable to happen.

Ordinarily towers should not be calculated, but they should be specified to stand certain loadings, and should be tested for these figures.

Foundations. It is very important in the use of rigid towers to see that the foundations on which the tower stands are all at the same height, and therefore, it should be specified that the foundations of the tower should have their tops within 1/10 of an inch of the same height.

Minimum Thickness of Material. In the construction of towers no material should be used less than 3/16 in. (4.7 mm.) in thickness.

Bolted Connections. It is recommended that the minimum number of bolts in any connection be not less than two.

Strength of Members. It should be kept in mind in the design of the towers that men are likely to climb up and down the towers on the angles, and therefore, one of the limiting conditions is to see that no members are used which would be bent by the weight of a man in so climbing a tower.

Movement of Wires. It would seem advisable to increase the customary figure of 45 deg. used for angle of deflection of the insulators to 55 deg. or 60 deg. from vertical, under the worst wind conditions.

The effect of ice and sleet should be considered, and this from the point of view of non-uniform loading. The structure should be so designed as to permit the loading of one span with the two adjacent spans not loaded, and still have sufficient clearance between all the wires so that under these conditions there would not be probable contact due to wind conditions.

Amount of Sleet. Not less than ¾ in. (19 mm.) of sleet or ice for the northeastern part of the United States and the eastern part of Canada should be allowed for.

Wind Load. The wind load is heaviest at times of sleet, and it should be recognized that the sleet does not form uniformly around the wires, but that the section of the ice is more or less elliptical.

Wind Pressure. It would seem advisable to increase the amount of wind pressure for the eastern part of Canada and the United States to about 15 lb. (6.8 kg.) pressure per sq. ft. (0.09 sq. m.) on the round surface.

The usual method of erecting towers is to assemble them lying on the ground and then tilt them into place, which is apt to induce faults in them, hence it is very necessary that a careful inspection be made of them after erection, with a view to tightening up the bolts and examining the various members to see whether they are distorted.

In many cases towers have been provided with insufficient means for supporting and firmly holding the ground cables. The ground cable clamps should be quite long and have not less than four bolts so that the cables cannot possibly slip, allowing them to sag down in contact with the power conductors.

Galvanizing and Painting. From reports received from various quarters it appears that the galvanizing of steel towers is generally preferred to painting. Probably the manufacturers themselves differ more on this point than the users of towers. One manufacturer advocates painting because of the simplicity obtained in erection by having the sides of the towers assembled complete and riveted in the shops, only the cross members requiring to be bolted together in the field. Large pieces assembled in this manner cannot well be galvanized and painting must be resorted to.

Paint affords a good protection if the structures are periodically gone over and carefully scraped and cleaned before the paint is applied. It is very difficult, however, to reach all small interstices and pockets and these are the places where rust is most apt to occur. Superficial inspection frequently will not disclose rusting which may be occurring beneath the paint coating. There is no doubt that periodical repainting is more neglected than otherwise.

Galvanizing, on the other hand, practically eliminates worry and expense for maintenance, as it is electro-positive to iron. The galvanized coating has two functions to perform. In the first place, it is designed to keep the surface of the steel from coming into contact with water and the atmosphere, and secondly, it protects the iron whenever water and oxygen finally succeed in breaking through.

If the galvanizing is properly done, it may be relied upon to be in good condition at the expiration of 12 or 15 years, whereas painting cannot be depended upon much longer than two or three years, especially where the atmosphere contains sulphur or other fumes.

Footings extending into the earth may be galvanized with good success in most soils, although there are earths where asphaltum paint coating is more durable. In cases where extreme acidity or electrolytic action is expected in the soil, it is more economical in the long run to provide a concrete footing thoroughly encasing the steel.

Conductors

The relative merits of copper and aluminum conductors have been discussed quite often and it is not our intention to open the subject again at this time. A thorough understanding of the different qualities of the two metals should be had by engineers designing transmission lines, especially where suspension

type insulators are considered, in order that advantage can be taken of these qualities. There are certainly places where aluminum should not be used for power conductors, but on the other hand, there are quite often cases where it might be used to better advantage than copper.

Experience has shown that hard-drawn copper cables should not have hemp centers, for an action partly chemical and partly mechanical is set up which sooner or later weakens the strands and causes the cable to part.

In order to secure a greater strength and also partly to add weight to the cable a steel core has been inserted in some of the aluminum cables recently manufactured. While it is claimed by the makers that such cables are as durable as the ordinary aluminum cables and free from electrolytic corrosion, conclusive proof upon this is still lacking. It is understood that steel cores in aluminum cables are not considered satisfactory by English cable manufacturers.

For long spans where great strength is required, wires and cables made of steel having a coating of copper (copper-clad steel) are available, which give very good results. These wires are still too high in cost to be used generally for power conductors. They are coming into use to a certain extent, however, for telephone and telegraph lines.

In passing, it may not be out of the way to remark that there are several formulas in existence, all more or less tedious in their application, for the calculation of cable sags, taking into account temperature changes as well as spans and tensions. The majority of these are adaptations of the parabola formula and will give sufficiently accurate results so long as the spans and sags are moderate. We would suggest that some simple method, such as a set of curves, be evolved, based preferably on the catenary, from which the sags may be quickly and accurately determined for all possible conditions.

Ground Wires. It is generally agreed that overhead ground wires are beneficial as a protection against lightning. Just how much protection is actually afforded, however, is still a mooted point. A report given below, on this subject, from one of the large companies in the West, well illustrates the feelings of a majority of operating engineers.

This company has about 450 miles (724 km.) of 60,000-volt pole line without overhead ground wires, and about 100 miles (160 km.) with the overhead ground wire.

In the case of one particular branch about 42 miles (67.5 km.) long, running northerly, we feel that we have had reliable and conclusive evidence that the overhead ground wire does protect. We have had a number of thunder storms cross this line at right angles, and while lightning would sometimes cause the automatic oil switches to open at the power station, yet no real damage occurred to either the line conductor or insulators, neither were the poles split by the lightning discharges. In other words, service could be re-established at once. On the other hand, these same storms would sometimes destroy pin type insulators and pole tops, on lines not protected with the overhead ground wire, and the general opinion has therefore been formed that the overhead ground wire does protect against material of the line being destroyed. However, we do not have either the number or severity of lightning storms that a large portion of the states do. We have, on all new work permitting the expense, equipped our lines with the overhead ground wires.

We might add, however, that the testimony is not altogether in one direction. While we have had very good direct evidence of the usefulness of the ground wire in one line, on another line we have had several insulators shattered, notwithstanding two ground wires on the top of a steel tower transmission line. These troubles, however, have been due to what we are quite sure have been direct strokes of lightning.

Insulators

Reports received from various parts of the country indicate that the suspension insulator as usually manufactured, in the disk type with metal caps and pin, is quite satisfactory when new, accomplishing the purpose for which it is intended, up to voltages of at least 150,000. The fly in the ointment, however, is that after they have been a year or two in service, failures begin to occur, and as time goes on a large number of the sections have to be replaced. To insure steady service on the lines the insulators have to be inspected at frequent intervals to weed out any that have become faulty. This trouble is not confined to any make of insulator nor to any section of the country. Extracts from reports from several companies are given herewith which will serve to show how prevalent the difficulty is and the means employed for inspection. The first report deals with conditions encountered on the lines of two or three companies in the South.

The Carolinas experienced very severe lightning during the past summer. Following repeated failures of insulators in a limited portion of a certain line, under the writer's observation, it was believed that there might exist insulators which were punctured, but of which no external signs were visible.

The line in question consisted of a single and double circuit steel tower line, equipped with suspension insulators and one ground wire.

It was accordingly determined to see if it was possible to locate any such punctured insulators by means of a megger.

A megger was secured, giving 500 volts, and reading 1000 megohms. The method of procedure was as follows:

On a single-circuit tower line a party was organized consisting of engineer in charge of megger, and six linemen, working in pairs. One pair would proceed to ground the line on a certain tower and hold the leads of the megger, which consist of about 100 ft. (30.4 m.) of standard lamp cord, to the individual disks in the strings of insulators, by means of two wood handles. The readings would then be taken, whereupon the megger would be taken to the next tower, on which another pair of men were ready to go through the same procedure. With this arrangement about four towers per hour could be tested, each tower being provided with eighteen disks.

On a double-circuit line about 26 towers were covered in ten hours.

The following results were obtained:

On a total of 2100 disks under observation, 14 of this number were found defective.

Twelve disks had defects invisible from the ground, and in two disks the defects were visible from the ground.

Of the twelve invisible from the ground, two of these could be noted as defective from the tower, four could be detected by very close inspection, after taking down, and six showed absolutely no defect.

One of these disks, the defect of which was entirely invisible, measured 300 megohms, two measured 250 megohms, and the balance were less than five megohms, which was the lowest point on the scale. Good disks were considerably over 1000 megohms.

Insulator failures with reference to their location on line, and relation to ground wire:

On a 100-kv. line, protected by ground wire, of a total of 94 failures of disks, it was noted that 28 were on the top wire, 25 on the middle wire, and 40 on the bottom wire.

Insulator failures in reference to steel towers vs. wood poles:

Insulator failures were compared on the following basis:

100-kv. tower line..... 35,770 disks
Failures..... 94 "
(Wires arranged vertically, single and double circuit, one ground wire)
60-kv. tower lines..... 2440 disks
Failures..... 4 "
(Wires arranged horizontally, single circuit, one ground wire)
60-kv. wood pole line..... 14,850 disks
Failures..... 4 "
(Wires arranged on right triangle, single circuit, one ground wire)
60-kv. wood pole line, using pin type insulators. 5718 insulators
Failures..... 1 insulator
(Wires arranged in right triangle, single circuit, no ground wire.)

The suspension disks are 10-in. (25.4 cm.) corrugated, single piece porcelain. The pin types are four-part, 14 in. (35.5 cm.) diameter, 12½ in. (31.9 cm.) high.

In connection with these failures it should be noted that the 100-kv.

line is equipped with six disks per string and the operating voltage is between 95 and 100 kv. The 60-kv. lines have three disks per string and operate at from 60 to 65 kv. The pin type insulators operate at 60 to 62 kv.

Probably one-third of the failures on the 100-kv. line occurred when the line was dead and the two ends of the same grounded. Of the four failures, on the 60-kv. wood pole line, using suspension insulators, three of these occurred while the line was temporarily operating at 22,000 volts. The pin insulator failure occurred while the line was dead and all three wires grounded at one end. The question arises, after considering these failures, whether there is any use in having more disks than are required to give a reasonable factor of safety on insulators, and also whether wood crossarms on steel towers should not be seriously considered.

Next follows a report from a California company.

Regarding the experience of the Southern California Edison Company with high-tension transmission lines, this company built a transmission line of 70,000 volts and about 120 miles (193 km.) long.

The towers are of steel, and a pin type insulator was used, being 18 in. (45.6 cm.) in diameter. These insulators were carefully tested out in the factories in the East, and were of three different makes.

These insulators gave absolutely no trouble for a period of at least one year, and the only line trouble experienced was due to eagles grounding the wire to the steel towers. However, after the second year had passed we began to experience considerable puncturing of insulators, and a careful inspection disclosed many insulators which were honeycombed with minute cracks. The line was very carefully gone over, each insulator being struck with a piece of hickory wood; this being the method used in testing fine porcelain ware in the china shops. All defective insulators were carefully culled, every one not ringing true being at once removed. We sometimes found indications of cracks on the rim of the insulator, but as a rule on one or the other of the petticoats. During the past five years, I have brought this matter energetically to the attention of the porcelain manufacturers, and have always insisted that the porcelain of the insulator shows an apparent aging, the cause of which we have been unable as yet to determine. This may be due to the extreme changes of temperature, to the continual vibrations of the wire, or perhaps a combination of the two; at any rate the aging of these insulators is going on with increasing rapidity, and every inspection of the line means the finding of hundreds of defective insulators which were in good shape the year previous.

In changing these insulators over (which work is going on at present) all are being replaced, both good and bad, with the suspension type. We have endeavored to use a few of these large 18-in. (45.6 cm.) insulators on some of our local 33,000-volt lines, with the idea that they would be serviceable in sections where the salt from the sea rapidly encrusts them; but even at this low potential we have had many of them break down electrically, showing that the insulators which originally stood the test for 100,000 volts were rapidly becoming wholly unfit for any of the high-potential work.

Our experience with the suspension type insulator has been too limited

to warrant us in giving an opinion as to their superiority over the pin type, but on our 60,000-volt line, four insulators in series, extending from Long Beach to Colton, a distance of approximately 80 miles (128.7 km.), we have discovered a great many broken insulators; especially when used as strain insulators. These were evidently broken by extra mechanical strain, and showed no exterior indication of injury. We, however, are watching this very closely, and have gone to the expense of changing the sets of insulators, taking the old ones back to our laboratory for test. As stated above, there appears to be a continual aging of all porcelain insulators going on, and they seem to be short-lived. Whether this is due to the combination of electrical and mechanical strain, I am unable as yet to say.

The following report by another engineer is along the same lines.

Experiments in the method of eliminating defective insulator sections by tests of insulation resistance with a megger have been conducted on the 100-kv. lines of the Yadkin River Power Company in North Carolina and upon new insulators in Utah intended for erection on the 130-kv. lines of the Utah Power & Light Company.

The Yadkin River Power Company operates 96 miles (154.4 km.) of double-circuit 100-kv. line from the Blewett Falls generating station to Raleigh and connecting through to the Southern Power Company at Durham, and also a 56-mile (90.1 km.) single-circuit line from Blewett Falls to Lumberton. This latter line is supported in part by single-circuit towers and in part by double-circuit towers carrying also a 22-kv. circuit. The conductor is three-strand No. 1 B. & S. copper. There is one overhead grounded cable and the insulators consist of six 10-in. (25.4 cm.) disks of the usual type. This line traverses a district subject to lightning storms of unusual and even extraordinary severity. During the past summer, the first lightning season of the line's service, there have been numerous cases of insulator trouble. Nearly all of the trouble has been experienced over a short section of about six miles (9.6 km.) length. The section is in open country and contains no angles or special features of construction, and no explanation of its especial susceptibility is obvious except that the storms appear to be of greatest severity in this vicinity. Failures have occurred usually on insulators supporting the top or the bottom conductor. The top conductor changes to the bottom at a transposition point in this trouble section.

The failures have been almost all of the same character; a disk will be punctured through the head, inside of the cap, the puncturing will be accompanied by an explosion which will blow considerable porcelain from the cap, causing the disk to separate and allowing the line to drop. The disk usually affected is the lowest of the string.

The load at Lumberton is mainly cotton mill power and no power is taken on Saturday afternoon and Sunday. On Saturday and Sunday, August 16 and 17, megger tests were made of all of the disks on 28 towers, covering between three and four miles of the section which has been experiencing trouble.

On the 28 towers were 94 strings of six disks each, or 564 disks. The disks were tested one at a time. Thirteen disks or 2.3 per cent were

found to be defective, the 13 disks occurring in 12 strings. Of the 13 punctured disks, two would have been apparent from the ground, since the disks were broken; six could have been discovered by close inspection after climbing the tower, since there were cracks in the metal insulator cap; three could not have been observed from the tower but would be apparent after taking down the insulator; and in two cases the disks did not show any visible evidence of having been punctured, although the megger showed them to have no insulation value.

Although these tests were on a very small scale and there has been no subsequent opportunity for continuation of them, yet they indicate that frequently a string of insulators will fail gradually, one disk at a time, and that a considerable measure of protection may be secured by periodic elimination tests with a megger, provided lines may be taken from service for the tests.

In Utah experimental tests have just been started on insulators not yet erected. The first reported test was as follows:

A. 400 10-in. (25.4-cm.) disks were tested and found good.

B. 100 10-in. (25.4-cm.) disks of another make were tested and found good.

C. 264 pillar insulators each consisting of three 10-in. (25.4 cm.) disks were tested; 26 insulators contained one bad disk each and two contained two bad disks each, a total of 12 per cent bad insulators or 4 per cent bad disks.

The insulation resistance of the defective disks ranged from 550 megohms to a value below the scale of the megger, which was one megohm.

D. 12 pillar insulators of another make, each consisting of eight 14-in. (35.5-cm.) disks, were tested and one disk found bad. The insulation resistance of this disk was about 25 megohms.

The defective insulators had been subjected to a factory high-potential test before shipment.

Three of the low-resistance 10-in. (25.4-cm.) disks in the pillar insulators mentioned above were subjected to a high-potential test and all failed, although at such voltage values as to make it seem possible that some would have stood up for a considerable period in service before actually puncturing. In the case of two others of the low-resistance disks, the metal caps were drilled off, but no cracks or visible defects were found. In general, it seems probable that clean insulators which have the low values of insulation resistance noted above will not stand high-potential service, owing to the local heating which would inevitably result.

These Utah tests are being continued with a view to determining the advisability of making such tests of all of the insulators on hand before putting them into service.

It is planned to incorporate a megger test in the specifications for all future insulator orders.

At voltages around 110,000 and even somewhat higher, there seems to be no reason for providing protection for the end units of suspension insulator strings to equalize the voltage gradients over the whole. There will doubtless come a time, with higher

voltages, when such protection will be needed, and experiments have been made which demonstrate the efficiency of end shields for this purpose. These shields act simply as electrodes for equalizing the electrostatic field in the region occupied by the insulators. Shields should present smoothly rounded surfaces and edges and need be no greater than 12 to 14 in. (30.4 to 35.4 cm.) in diameter to produce good results. With these shields may be mounted arcing rings or tips to keep arcs away from the insulators, as found necessary.

Clamps and Fittings

There are several types of clamps on the market intended to secure the line conductors to suspension and strain type insulators. These all perform this function very well insofar as they do not allow the conductor to slip. Some are so severe, however, that the cable is mashed and unfit for taking strains if the sags ever have to be readjusted, by no means an uncommon occurrence. Practically none of the clamps are designed with smooth outlines or with an idea of avoiding more or less sharp projections which cause static discharges at the higher voltages and which concentrate the electrostatic field in that vicinity.

Notes on Station Apparatus

Rapid improvement has been made in the design and construction of transformers since the advent of the higher voltages. It was a comparatively simple matter to build a transformer for 60,000 volts which would stand up under all manner of severe service without ever giving any trouble, even when used with a large generating capacity back of it. Transformers built along the same general lines with more insulation were then tried at 110,000 volts, but trouble developed almost at once, sometimes through the short-circuiting between turns of the windings or else at tap points, and quite often by the distortion of the coils under short-circuit conditions. It was then recognized that because of their different physical constants, the higher voltage transformers were, so to speak, much more susceptible to line disturbances such as switching, etc., than those for lower voltage, and the designs have been changed accordingly, much attention being given especially to the bracing of the coils. The greatly improved results which have been obtained since these changes have been carried out, testify to the soundness of the principle of strengthening apparatus against failure rather than the *spending of large* sums on protective devices of various kinds.

An important problem for distribution companies serving sparsely settled districts, especially those in the West, is that of securing small high-voltage transformers, three-phase or single-phase, which will stand up under the line switching, surges, etc., which occur in ordinary operation of a large high-tension system. The companies must generally reach out for all possible load wherever it may be, and it is of prime importance that this subject of small high-tension transformers should receive the greatest possible consideration, as the services usually secured by their use pay the highest price for energy, making it possible for any company to extend its lines to be ready for the business as the country develops. Such transformers only, will make it possible to serve the farming community, which, it is claimed by some, offers the most attractive income now in view for operating companies, because of the fact that once the farmer is connected to the lines, he will remain a customer with increasing energy consumption, with good load factors, and furthermore, the general expense of service, such as collections, moving meters, etc., is very much reduced with this class of service, in contrast to the floating population of a great many cities.

Oil circuit breakers are becoming more reliable for high potentials and heavy service, but it is still unwise to attempt to rupture short circuits close to the generators when their combined normal capacity is much greater than 50,000 kw.

While it is generally believed that the electrolytic lightning arresters, as at present developed, are the best in their line that the art affords, it is still quite difficult to make any definite qualitative statements in respect to the protection they actually afford against lightning or other disturbances. Certainly no one would care to take the responsibility of operating stations without arresters, for they are considered to be a form of insurance against trouble; but it would be desirable to have more light on the subject.

Interferences with Telephone and Telegraph Lines

This is a subject which has been given but little attention, although the problem is a very important one. Nearby telephone and telegraph lines are sometimes made inoperative when any disturbance exists on the transmission line.

A good part of the trouble of the telephone service is due to insufficient insulation. Some of the lines, before long-distance

transmission was inaugurated, ran through and touched the branches of tree tops, which caused leakage in wet weather, and hence unbalanced the wires.

With the troubles due to poor insulation overcome and the transmission line well balanced, no further trouble was encountered except at times of disturbance or interruption on the transmission line. With grounded systems this resulted in the burning out of telegraph relays and blowing fuses on the telephones.

A much more difficult matter to deal with is the making of the transmission company's own private telephone to operate at all times. Usually the telephone line is needed the most at times of trouble and this is just the time when it is out of service, having been put out of commission by the trouble itself.

When providing protection for a recent telephone line paralleling a high-voltage system for a distance of some 300 miles (482.8 km.), it was found that there is no protective apparatus on the market capable of handling the large induced currents which are always present on such lines.

Thus the apparatus had to be built, and was of a very substantial character. The basic principle which was worked upon was to make the line subject, in the first place, to as little trouble as possible by carefully insulating and balancing it with respect to the transmission line circuits. This meant that transpositions had to be placed at frequent intervals. Furthermore, no twigs or other objects were allowed to come into contact with the wire. The usual grounding coils, but designed specially for this purpose, were cut in at each station. By these means alone the line was rendered quiet, even though within 60 ft. (18.2 m.) of the high-voltage wires, and conversation could be carried on over a distance of 125 miles (201 km.) with greater satisfaction than over the paralleling commercial circuits. Much heavier fuses were used, for it was not permissible to have them blow out when the circuits were needed most. Discharge gaps were provided, some of these being in vacuum, which gave very good results. The other protection consisted of condensers and choke coils for absorbing the smaller disturbances which would make conversation more or less unsatisfactory. It must not be understood, however, that any or all of these means can be guaranteed to produce a quiet working line, for each case must be studied by itself and methods adopted to meet the conditions.

APPENDIX I—DETERIORATION OF PORCELAIN INSULATORS IN SERVICE

BY J. A. BRUNDIGE

While it has been recognized practically since the inception of the electrical art that the commoner insulating materials, such as rubber and compound treated fabrics, are subject to more or less rapid destruction when under the influence of continued electrical stress, the more solid insulating bodies, like glass and porcelain, were looked upon as being permanent in their characteristics and it was considered that they could be relied upon indefinitely to perform their functions. This idea in the minds of engineers has persistently held, even though a few pioneers a number of years ago suggested that it was not impossible that glass and porcelain might be subject to a molecular fatigue when acted upon by electrical forces for long periods, similar to that exhibited by metals under repeated mechanical stresses. Now it is safe to assume that the majority of operating engineers, having to deal with higher voltage transmission lines, have had experiences which lead them to believe in the theory of electrical fatigue in porcelain. Whether this comes about solely through the continued application of the normal operating voltage or whether it is due to the transient overvoltages which are unavoidable on any line, is hard to say, but the existing evidence points to the latter conclusion.

It must not be understood that all or even the greater portion of the failures experienced with suspension type insulators are due to molecular deterioration of the porcelain. A large number of the failures have been traceable to improper design of the insulator parts or to an unsuitable porcelain body.

It has been the experience of a number of transmission companies to have practically no insulator trouble for the first couple of years of operation; then the insulators began to fail in increasingly greater numbers, for no apparent reason. Closer examination, however, sometimes revealed the fact that minute checks had formed all over the surface of the porcelain, and that the failure had been due to a crack extending clear through the shell. This behavior of the porcelain has not been confined to any kind or type of insulator nor to any one manufacturer's product.

The principal requisites for a good porcelain for high-voltage insulators, are high dielectric strength and mechanical toughness. These two qualities are somewhat opposed to each other

in the actual manufacture, for when a high dielectric strength is obtained, the porcelain is apt to be brittle like glass. It is possible, however, to arrive at mixtures which exhibit both properties to a marked extent when the firing has been properly done, although it is regrettable that some so-called high-voltage porcelains appear to be lacking in both of these properties.

This can be better understood when it is learned that the mixtures used by two prominent manufacturers, each putting out a product which is accepted as reasonably good, vary greatly in the proportion of ingredients employed. While the felspar contents of the two mixtures are of the same order, one has twice as much flint as the other, and the quantities of ball clay and china clay vary as much as three to one. Yet the different manufacturers regard their mixing formulas as trade secrets, and the proportions are religiously followed down to tenths of one per cent. This latter is doubtless done for the sake of uniformity of product, which is important, but until the mixtures more nearly approach a recognized standard, it appears that more or less trouble may be expected with high-tension insulators.

Doubtless, the factor having more to do with the failure of insulators than the porcelain body is the design; or in other words, not only must the electrical characteristics of the insulator, such as puncturing and flash-over values, both of which are highly important, be considered, but also the size and shape of the parts as well. With certain pin type insulators, especially those mounted on metal pins, cracks have been observed in quite a number of the petticoats. These were evidently expansion effects due to temperature changes. The same effects have been noticed to a greater extent with the suspension type insulators provided with metal caps and pins. We have here porcelain, cement and iron assembled together, the coefficients of temperature expansion of the three being quite dissimilar. In this latitude the temperature variation between summer and winter days is well in excess of 100 deg. fahr., and it can be appreciated that enormous internal strains must be set up inside of the caps. The porcelain being the least able to withstand these forces, is the part that suffers and cracks, with the attendant electrical punctures ensuing. In the case of an insulator designed for high mechanical strength in tension, which necessarily means a rather high cap with correspondingly long pin, the temperature changes cause a marked var-

iation in the length of the pin which is in contact with the porcelain through means of a layer of cement for a distance of sometimes 2½ to 3 in. (6.3 to 7.2 cm.) along its length. The great strain to which the porcelain is subjected is then apt to produce cracks perpendicular to the axis of the pin, which has actually been found to be the case in a large number of instances. These cracks, however, are mostly very minute and can hardly be detected by the eye if the cap and the cement have been carefully removed. A line of ink drawn over the surface of the porcelain, however, will nearly always disclose the cracks, as the ink will be drawn along them by capillary action.

The method of failure of suspension insulators with metal caps and pins is often quite characteristic. Cracks develop at some point inside the cap, and when the current leakage through them is sufficient, a path is fused through the porcelain by the intense heat generated. If the heating takes place relatively slowly, a hole is apt to be fused through the cap, through which gases and melted porcelain are forcibly expelled, but the insulator usually holds together and continues to support the cable. With a large amount of power back of the break, which may act in the nature of a short circuit inside the insulator, caps have been known actually to explode, in which event the line conductor is allowed to fall. Before the burning of the caps can take place, it is necessary that several of the units of an insulator string be bad, and instances have been observed where all the caps of ten-unit insulators have been so affected. With the better methods for locating cracks and faults as soon as they have developed, such as the high-range megger, the pyrotechnic displays above described have become fewer.

Because of several instances of trouble of this character having recently been observed in connection with suspension type insulators, some engineers have been led to believe that they are unsuccessful, which conclusion is wholly unwarranted.

The high-range megger has proved to be an extremely useful instrument for the locating of insulator faults undiscoverable so far as ordinary means of inspection are concerned. Tests made on a large number of units later checked up by tests with a high-tension transformer, have shown that the megger can be absolutely depended upon if reasonable care is used to see that there is no leakage in the conducting leads. To show the sensitiveness of the megger, the two electrodes can be placed within ¼ in. (6.3 mm.) of each other on a glazed porcelain sur-

face or upon a fractured surface where there is no glaze and the reading will be practically infinity. By blowing the breath upon this surface even when the porcelain is at a moderately high temperature, the moisture so deposited will be sufficient to give a comparatively low reading on the needle. When a crack occurs in the porcelain up inside the cap there is always sufficient moisture present in the cement to give an indication on the needle, which need not be confounded with surface leakage, if the insulator is at all reasonably clean. If the insulators are so dirty that surface leakage is marked, they should be cleaned before the megger test. Certain insulators may give a reading of from 40 to 100 megohms, and if later tested with a high-tension transformer they will not fail immediately upon the application of voltage, but may hold up until 30,000, 50,000 or even 60,000 volts is reached before puncturing. Those which show a zero reading on the megger will stand no voltage from the testing transformer.

An interesting experiment was recently made by immersing a batch of insulators in water at ordinary temperature and slowly bringing them up to the boiling point. Twenty insulators, some two or three years old, were tested in this manner and every one was found to be ruined by the time boiling point was reached. These were from two different manufacturers, one of whom has previously delivered batches of insulators where bringing them to the boiling point of water was one of the routine requirements before the insulators left the factory. Other similar tests made on new insulators of the same design did not produce failure, except in a few units. The probable explanation of this is that in the new insulators the cement had not yet attained its ultimate hardness, and allowed the expansion to take place in the pin without cracking the porcelain.

The data at hand upon insulator failures are unfortunately very incomplete, and until these are collected and have been studied, all designs brought forward must necessarily be lacking in some respect. Enough is already known, however, to indicate the general direction which the new designs will follow, and it may be confidently predicted that the troubles experienced will be materially lessened in the immediate future.

APPENDIX II—RADIUS OF INFLUENCE OF A DIRECT LIGHTNING STROKE

BY L. C. NICHOLSON

A lightning stroke to earth at some point adjacent to a high-tension transmission line induces voltages and frequencies in the transmission conductors of sufficient magnitude to affect the insulation of the line, causing either spill-overs or punctures of insulators. The question often arises as to how near the line lightning can strike without affecting its operation. The answer to this question can never be definite, since not only do transmission lines vary in degree of both insulation and lightning protection, but the character and severity of lightning strokes undoubtedly vary between wide limits. General atmospheric electrostatic conditions also have an effect.

Through continued personal inquiry it is possible to arrive at a general estimate concerning the radius of influence of a direct lightning stroke. By noting objects which have been struck by lightning adjacent to transmission lines and comparing the operation of the line at the time the object was probably struck, an opinion can be arrived at, which is applicable to a particular transmission line located in a given lightning belt. Such an opinion undoubtedly would have to be modified considerably to apply to transmission lines of different insulation characteristics and lightning protection and exposure.

Observation and inquiry lead to the following general conclusions on this subject.

1. It is doubtful if any degree of insulation in use at present, with or without the ordinary protective measures, will withstand the effect of a direct stroke of lightning on the line. In such a case the electromechanical forces acting on the porcelain are very high, usually causing insulators practically to explode. It is not unusual in such cases to find insulators shattered into small fragments, many of which are thrown as far as 100 ft. (30.4 m.) from the line. Furthermore, a direct stroke usually envelopes all the conductors of a line and sometimes envelopes several lines located relatively close together. This would indicate that the area of the stroke itself is large, or that it has numerous prongs. Observation of burn marks on conductors which were struck when there was no power on the line indicate by their distribution and extent that the diameter of the stroke was approximately 20 ft. (6 m.) Such being the case it is not surprising that one or more overhead ground wires cannot always intercept direct strokes.

2. Induced effects from strokes at some distance from the line may, on medium-voltage lines, be of sufficient magnitude to cause flash-over or puncture of insulators. Extended observation of the operation of 60,000-volt pin type insulators, unprotected by overhead wires, leads to the estimate that the radial influence of direct strokes is rarely in excess of 2000 ft. (609 m.) and may be less than 100 ft. (30.4 m.). These are rather wide limits, but the most definite evidence available indicates their probability. It appears that strokes of great severity, 2000 ft. (609 m.), and more in extreme cases, from the line, produce disturbances of operation, while strokes of less severity may occur at 100 ft. (30.4 m.) from the line without producing such results. These last are, however, in our opinion, rare, and a stroke at less than 2000 ft. (609 m.) from the line is apt to cause trouble.

In more highly insulated lines the danger zone apparently decreases substantially, and in the most highly insulated circuits at present in operation it is probable that the large majority of induced effects are insulated and protected against, leaving only direct strokes on the line itself to be taken.

Careful numerical tabulation of lightning effects indicates that direct strokes on the line constitute approximately 10 per cent of all lightning disturbances on 60,000-volt pin type circuits located in New York State.

APPENDIX III—TRANSMISSION LINE PROBLEMS IN THE WEST

BY P. M. DOWNING

The different power companies operating on the Pacific Coast have done a great deal in the way of pioneer work in the transmission of power over long distances at high voltages. This was due, to a considerable extent, to the fact that there is an abundance of water available for the hydroelectric generation of power, and also to the fact that the cost of fuel is very high as compared with that further east.

The first long-distance transmission to be put into successful operation on this coast, if not the first in the United States, was that of the San Antonio Light & Power Company in southern California, at what is known as their Pomona plant. This transmission was for a distance of 30 miles (48.2 km.) at 10,000 volts.

Transformers were at that time not manufactured for such high voltages, and it was necessary to connect in series ten 1000-volt transformers for stepping up. The low-tension windings were connected in multiple.

The first polyphase installation was made in 1893, at Mill Creek, and furnished power to the city of Redlands.

The success of these undertakings gave a great impetus to the hydroelectric industry, and inside the next five or six years, there were several different companies operating at voltages as high as 60,000.

The climatic conditions of the Pacific Coast, and particularly of California, are most favorable to the operation of high-voltage lines. Except in the higher mountain districts, there is practically no snow to contend with, and there are but very few places where lightning ever causes any trouble. Some operating companies have installed lightning arrester equipment, but it is not common practise to do so. The well-known horn gap arrester, one side of which is connected directly to ground without resistance, has in many instances been used to advantage, more as a voltage-limiting device than as a lightning arrester. These have proved quite satisfactory for this work. Ground wires strung above the line wires have been used to some extent, but there is so little trouble from lightning that engineers have never been able to decide as to whether or not there is any advantage in using them.

Very seldom, if ever, is it possible to find where an insulator has been punctured due to lightning. This is, possibly, due to the fact that the high voltage dissipates itself over the surface of the insulators. Many instances are known where lightning striking the line has burned off one or more wires between poles, and gone to ground without in any way damaging the insulators, and only slightly damaging the wood poles.

The greatest trouble on lines using the ordinary four-part, 14-in. (35.5 cm.) pin type insulators at voltages around 60,000 is that due to leakage over the insulator. The climate of this coast is peculiar in that there are two seasons, one being dry and lasting for six months, the other being wet. During the dry season, and particularly in the sections near the coast, dust and salt fog accumulates on the insulators to such an extent that leakage eventually burns off the pole, and sometimes the line wires, without damaging the insulators.

Different ways of overcoming this trouble have been tried.

Cleaning the insulators does some good, but does not entirely eliminate the trouble. After the first heavy rains come on in the early winter, the insulators are washed off and less trouble is experienced during the rainy season than at other times.

Ungrounded metal pins connected together electrically give very much less trouble than where they are not so connected, or where wood pins are used. Grounding the pins has been tried with unsatisfactory results because of arcing over the insulator. When once so established the arc will hold until the voltage drops.

The regulation of voltages on a high-tension network is not always an easy problem. No one particular point can be selected at which voltage can be kept constant, but it is necessary to keep it as nearly uniform as possible over the entire system. This is accomplished by the use of synchronous condensers located at the more important distributing centers.

These condenser regulators can be made automatic by using contact-making voltmeters, relay switches and motors to control the field rheostats; in other words, by the use of auxiliaries similar in every respect to those used in connection with the well known automatic induction regulator. A number of such installations have been in satisfactory operation for several years.

The first high-voltage oil switches were constructed and put into operation in California. The same general type and design that was originally selected as being suitable for 40,000 volts is, with slight modifications, still being used on 110,000-volt lines. In this particular switch the circuit is opened at two or four points, depending on the voltage and load carried. The contacts are made by rotating blades moving in a horizontal plane. The separate oil containers for each leg of the circuit are insulated from each other and from the ground by means of properly designed porcelain bushings or insulators.

Another very successful design of switch for the same character of service is that using a pantograph arrangement of links carrying contacts, thus giving a break in a vertical plane. Both of these types of switch have for years been in successful operation under all conditions of load. They have a weakness common to all oil switches, in that when operated under heavy short circuits they will at times throw oil out of the container.

Outdoor oil switches, either automatic or non-automatic, are being used very generally for branch lines, or for sectionalizing trunk lines. For economic reasons the automatic switches are

very often operated by means of a solenoid placed directly in the main line. Such an arrangement does away with the use of current transformers, but has the objection that the connection from the movable plunger to the relay, or trip, must stand the entire voltage from line to ground.

As the sensitiveness of the trip is, to a considerable extent, dependent upon the weight of the moving parts, the importance of keeping this weight down to a minimum is apparent. Well-treated rods of sufficient length have been used to make the connection from the plunger to the trip, or relay, but they have not been entirely satisfactory, because sooner or later the leakage burns them off.

Transformer designs have more than kept pace with the art of long-distance transmission at high voltages, and it is now possible to get satisfactory apparatus for any voltage that can be handled on the lines.

One thing, however, that some manufacturers have failed to give proper attention to is that of supporting the windings to prevent injury or distortion due to mechanical strains set up when short circuits occur. In units of large capacities and high voltages, the coils are generally built of strap copper, using one turn per layer, these turns being separated by one or more thicknesses of insulating material. Obviously, with such a construction, the turns will be easily displaced, unless they are well supported on both sides.

A number of failures have recently occurred where straight vertical separating strips have been used in assembling the coils, thus leaving the turns between these separating strips unsupported throughout their entire length, and allowing them to be displaced when short circuits came on. Shorter strips placed diagonally across the coils, or wave-shaped strips, which will allow a free circulation of oil, will entirely overcome this trouble.

APPENDIX IV—SWITCHING

BY G. FACCIOLI

Switching produces, in general, an abrupt change in the value of the electromotive force and of the current of the circuit, or of either of these quantities, and therefore it produces a sudden change in the amount of energy stored in the circuit, with the result that oscillations are produced.

The severity of these oscillations depends on the difference be-

tween the running conditions before and after the switching is done. For instance, if a dead line at zero potential is suddenly connected to an alternating-current generator, the oscillation produced will be most severe when the switch makes the connection at the instant at which the electromotive force has its maximum value. Likewise, if a short-circuited line is disconnected from an alternating-current generator, the oscillation is most severe when the circuit is broken at the instant at which the current passes through its maximum value.

The oscillations are of two kinds: They may occur between inductance massed at one point of the circuit, and capacity massed at another point of the circuit, as, for instance, when a dead line which acts practically as a condenser is connected to a generator which acts practically as an inductance, or when a line (capacity) connected at one end to a step-down transformer (inductance) is disconnected from the generating system.

They may also occur between the distributed inductance and capacity of a part of the circuit, as, for instance, when a line is disconnected from a generator and the energy stored in the line gradually dies out, changing from electromagnetic energy stored in the distributed inductance of the line, to electrostatic energy stored in the distributed capacity of the line and vice versa, or when an unloaded step-down transformer is disconnected from the line, its windings acting similarly to a line.

These oscillations do not, in general, constitute a great danger to the circuit if the contact in the switch is made once, positively, for every switching operation.

However, if each switching operation is accompanied by arcs, so that the circuit is repeatedly closed and opened, then the pressure rises may become dangerous, and destructive cumulative oscillations may be set up in the apparatus. Furthermore, at the instant at which contact is made, traveling waves are sent out from the point of switching along the line in both directions. These traveling waves with steep fronts follow, naturally, the well-known rules of reflection and refraction, and whenever they strike a localized oscillatory circuit, they excite in it oscillations at its natural period.

For instance, if a dead line is suddenly connected to a live line having the same constants, a " wave of charge," equal in value to one-half of the potential of the live line, starts along the dead line from the switching point. If the dead line is open at the far end, the " wave of charge " is reflected back at double

potential, etc., etc. At the same time a " wave of discharge " starts along the live line from the switching point with a value equal to one-half of the original voltage of this line. If the live line is connected at its origin to transformers, this " wave of discharge " is reflected back with double voltage and may excite local oscillations in the transformer windings or in the circuits of the power house, etc., etc.

These traveling waves are a source of danger and obviously the danger is increased when sparking and arcing occur in the switch.

It is seen from the above that high-tension switching, which has lately gained so much importance in the art, should be done very judiciously and only when necessary, unless special precautions are taken to avoid the disturbances resulting therefrom.

As a rule, low-tension switching is preferable, as this avoids steep wave front phenomena.

For instance, in energizing a line, it is preferable to connect the dead line to the dead step-up transformer and then connect, by low-tension switches, the line and transformer to the generator, rather than connecting the transformer alone to the generator and then switching the line onto the high-tension winding of the transformer. Of course, in this case it would be still better to connect the line and the step-up transformer and the generator together while the whole system is dead and then bring it up gradually to full potential by the excitation of the generator.

Fuses act similarly to switches, except that the former open under load, while switches are, as a rule, operated at approximately no-load. The sudden interruption of large amounts of current results in considerable over-tensions, and this is the danger that usually accompanies the blowing of fuses.

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PRACTICAL OPERATION OF SUSPENSION INSULATORS

BY H. W. BUCK

ABSTRACT OF PAPER

The paper describes some of the mechanical and electrical problems which have been experienced on high-voltage transmission lines equipped with suspension insulators and points out some of the principles involved and some practical methods for guarding against the troubles. Figures are given showing the deflections which will take place, for various sizes of aluminum and copper conductors, at the insulators, under the pressure of maximum probable wind velocity.

THE APPLICATION of suspension insulators to high-voltage transmission lines, since their first introduction in 1905, has been very general on all lines operating at voltages over 50,000, and the results obtained have been in most cases very satisfactory. The change, however, from the rigid pin insulator to a construction involving the free and flexible suspension of the conductor in space is a radical one and the change in practise has taken place with considerable abruptness, so that it is not surprising to have experienced a new class of line troubles. It is the purpose of this paper to point out a few of the difficulties which have been experienced, with the hope that a discussion of the subject may lead to improved standards of construction for such lines.

In the pin insulator line the conductor is held rigidly at every insulator, consequently lateral and longitudinal movement of the conductor is resisted at every point of support. Suspension insulators, however, except at dead-end connections, are free to move in all directions. The result is that high winds occasionally cause displacements which are electrically and mechanically dangerous to the operation of the line. Deflections of suspension insulators from the vertical position result also from other causes, which will be discussed later.

Large angular deflections of suspension insulators require large clearance spaces, which necessitate long crossarms and increased cost of tower. Consequently it is desirable to limit the deflection as far as possible. A 60-deg. angle from the ver-

tical is assumed to be the maximum allowable under extreme conditions.

In order to show how nearly the above limitation can be attained in practise, Table I is given, indicating the deflections caused by wind pressure on various sizes of conductor, at the insulator. The wind pressure assumed in the table is 15 lb. (6.8 kg.) per sq. ft. (0.09 m.) of projected conductor area, which is taken as the maximum. Wind pressure deflections are practically independent of span length, since wind pressure per span and the force which resists the wind pressure, namely, the weight of the conductor, both vary directly with length, in the same proportion.

TABLE I

A Size conductor	B Wind pressure	C Angular deflection	D Auxiliary weight
	STRANDED COPPER		
4	15 lb.	66 deg.	0.041 lb.
3	15 "	63 "	0.028 "
2	15 "	60 "	0.0 "
1	15 "	58 "	0.0 "
0	15 "	55 "	0.0 "
00	15 "	52 "	0.0 "
000	15 "	49 "	0.0 "
0000	15 "	45 "	0.0 "
	STRANDED ALUMINUM		
2	15 lb.	81 deg.	0.156 lb.
1	15 "	79 "	0.161 "
0	15 "	78 "	0.171 "
00	15 "	77 "	0.182 "
000	15 "	75 "	0.186 "
0000	15 "	74 "	0.196 "
250000	15 "	72 "	0.190 "
300000	15 "	71 "	0.177 "
400000	15 "	68 "	0.158 "
500000	15 "	66 "	0.125 "

Experiments have shown that the weight of the string of suspension insulators themselves will not act to resist wind displacement of conductor, since the exposed surface of the insulators is sufficient to cause their deflection by wind pressure without the attachment of the conductor. Neither will the deflection vary appreciably with the size and design of the insulators, since a heavier insulator ordinarily exposes a larger "sail area." The wind displacement of conductor can therefore be assumed to be independent of the number of insulators in the string, and of their particular design.

Table I indicates approximately the wind deflections which will take place for various sizes of conductor under a stress of wind equal to 15 lb. per sq.ft., as above. Two tabulations are given, one for copper, and the other for aluminum.

In Table I, column A shows the conductor size in B. & S. gage. Column B gives the assumed wind pressure in pounds per square foot of projected cable area. Column C gives the angular deflection of the insulator from the vertical, due to the assumed wind pressure on the conductor, assuming that the insulator itself deflects independently and neither increases nor decreases the displacement of the conductor. Column D shows the amount by which the weight of the conductor would have to be increased in order to reduce the deflection of the insulator under the assumed conditions to within the 60-deg. limit.

It will be seen from an inspection of the table that all sizes of copper except the smallest sizes listed, namely, No. 4 and No. 3, will ballast the insulators sufficiently to keep the wind deflection down to within 60 deg. A line of No. 4 B. and S. wire, it will be noted, is deficient in weight to the extent of 0.041 lb. per ft. and No. 3, 0.028 lb. per foot.

On the other hand, all the sizes of aluminum cable listed will allow deflections in excess of 60 deg., and especially among the smaller sizes, objectionable displacements will occur. Under these conditions one of the chief supposed advantages of aluminum, namely, its lightness, becomes its disadvantage, and the actual ballasting quality of copper due to its higher specific gravity and smaller size is a distinct advantage.

The larger sizes of conductor are more stable mechanically against wind deflection, since their weight in proportion to the surface exposed to wind is greater than in the small sizes, the weight increasing as the square of the diameter, whereas the wind pressure is only directly proportional to the diameter.

Fig. 1 shows a method for reducing deflection which has been adopted on an aluminum transmission line in the South, about 200 miles (321.8 km.) in length, which has produced satisfactory results. The line is of No. 0 B. & S. aluminum cable, with an average span length of about 300 ft. (91.4 m.). An auxiliary weight made of cast iron is attached to the lower side of the suspension clamp at every insulator. It is consequently placed at a point where it is most effective as ballast. This arrangement results in very satisfactory stability of the line under all conditions.

Column D, Table I, shows the auxiliary weight which must be added at each insulator for the proper stability, expressed in pounds per foot of span. In the opinion of the writer, auxiliary weights of this kind should be provided on all aluminum lines using suspension insulators and on all lines where the smaller sizes of copper are installed. The auxiliary weight not only stabilizes the line against wind pressure but improves its operation in many ways, such as in resisting longitudinal movement of insulators under unbalanced pull due to a breakage somewhere along the line. It also improves conditions where a gust of wind strikes a single span independently, in reducing the slack which can be taken from adjacent spans due to unbalanced pressure.

A curious and unusual phenomenon has been experienced on at least one suspension insulator transmission line known to the writer, and is illustrated in Fig. 2. A severe sleet storm had occurred along the line during the night and all the conductors were covered with a heavy coating of sleet. When the sun came out in the morning the sleet started to melt, but it did not, naturally, fall off all spans of the conductors simultaneously. The condition illustrated in Fig. 2 occurred. Sleet has melted and dropped off spans B_1 and B_3, leaving span B_2 loaded and all other conductors in normal position, either sleet-covered or otherwise. Span B_2 will then sag down, taking slack from adjacent spans, and will come in contact with conductor C_2, causing a short circuit. Such a combination of circumstances, although unusual, might happen on any suspension insulator line where the conductors are disposed in the vertical plane, and should be guarded against.

On long tangents on a suspension insulator line where there are no dead-end connections installed, if a very high wind strikes the line at an angle of about 45 deg., cumulative waves like the waves on the surface of the water have been observed to travel along the conductors of the line, causing a whipping action at all suspension insulators, the waves finally "breaking" as on a beach at the first dead-end connection met. This phenomenon cannot occur on a pin insulator line, since the line is confined at every crossarm. This trouble can be prevented by dead-ending the line at frequent intervals.

The methods of dead-ending suspension insulator lines as at present practised cannot be considered satisfactory. There is a wide margin for improvement in the design of the mechan-

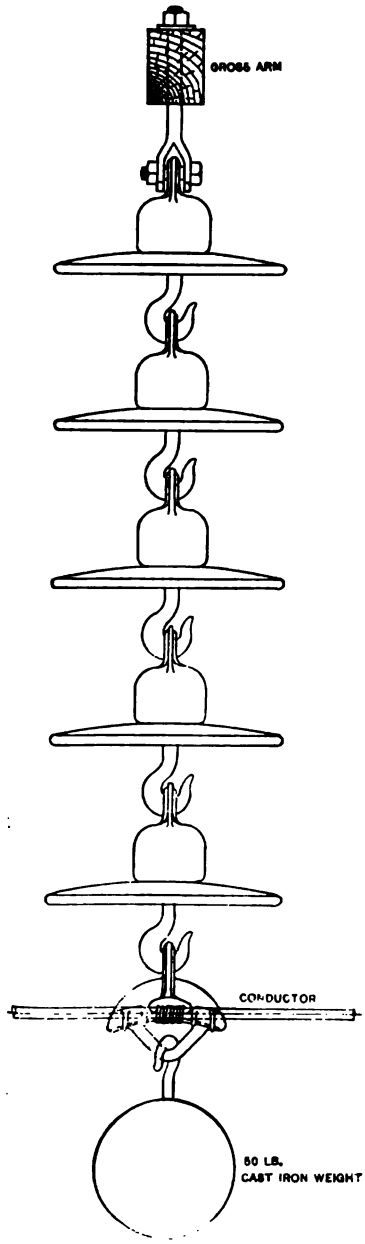
CROSS ARM
CONDUCTOR
50 LB.
CAST IRON WEIGHT

FIG. 1

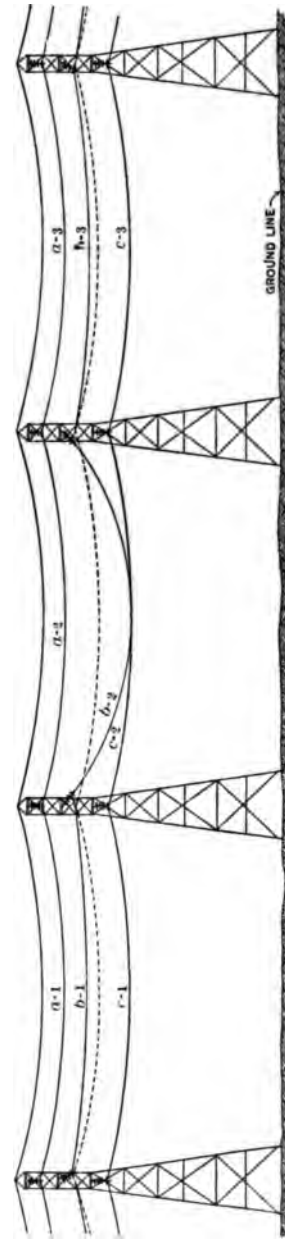
a-3
b-3
c-3
GROUND LINE
a-2
b-2
c-2
a-1
b-1
c-1

FIG. 2

ical fittings used for the purpose, especially in providing means for preventing the lateral swing of the jumper connection. Here, too, some form of ballast weight might be used to advantage.

In the experience of the writer the suspension insulator units which have given by far the best service over a long period of time are those of the simple general form shown in the assembly in Fig. 1. The design of these disks is entirely free from corrugations, flanges, petticoats, etc. While such devices increase the resistance of the insulator to surface leakage and surface arcing, the complexity of form seems to introduce internal shrinkage stresses in the process of moulding, firing and cooling, which in time, due to sudden temperature change or mechanical shock, will develop into puncturable faults. The insulator of simpler form is cheaper and more can be installed in series at the same cost and with the same electrical factor of safety as with a fewer number of disks of a more elaborate and expensive design.

In general, most of the troubles which are being experienced in the various suspension insulator lines built to date can be overcome by the following precautions:

1. Provide liberal clearance between conductors and between conductors and supports. This should be considerably more than good practise would require in a pin type insulator line.

2. Install the lightning ground wire, if used, high above the conductors, so that no combination of gusts of wind can whip the conductor into it when suspension insulators are deflected to the maximum angle.

3. Place auxiliary ballast weights at every suspension insulator where aluminum cable is used and with the smaller sizes of copper.

4. Design the jumpers and fittings at the dead-end connections so that the jumpers cannot possibly become displaced and come into contact with the crossarm.

5. Draw the conductor up reasonably tight throughout the line. A too conservative allowance of slack to guard against possible mechanical stresses in the conductor will cause more trouble than it will prevent.

The insulating properties of suspension insulators have proved adequate for all line voltages so far attempted up to 150,000 volts, and the satisfactory results have been attained within reasonable mechanical dimensions of insulators. The insulating

units shown in Fig. 1, which are about as small as any made, electrically or mechanically, being merely 10 in. (25.4 cm.) disks of plain surface, will arc over "dry" at about 80,000 volts and "wet" at about 50,000 volts. The arc-over voltage is well under the puncture voltage. Insulating units of more elaborate design will withstand considerably higher voltage tests. Mechanically, such insulators will withstand tension stresses of at least 5000 lb. (2268 kg.)

In determining the proper number of disks to be strung in series it is advisable to install the number required for the desired factor of safety and then to add at least one disk for reserve against breakage. In other words, the insulator should have a sufficient number of disks in series so that in case one or more are broken or punctured the remaining intact disks will afford a sufficient margin of insulation for safe operation until such time as the broken disks can be replaced.

On this basis, assuming an insulation factor of safety of two, an 80,000-volt line would require four of the disks of Fig. 1, 100,000 volts, five disks, and so on for higher voltages. These results are interesting for comparison with the probable cost, mechanical dimensions and strength of a pin insulator which might give equivalent results.

DISCUSSION ON SUB-COMMITTEE REPORT ON "PROBLEMS OF HIGH-TENSION TRANSMISSION LINES" (SOTHMAN AND OTHERS), AND "PRACTICAL OPERATION OF SUSPENSION INSULATORS" (BUCK), NEW YORK, FEBRUARY 26, 1914.

H. W. Buck: I want to corroborate what has been said in regard to the sag table. It is one of those engineering problems which are worked out in the office in accordance with certain theoretical laws which are apt to be more or less disregarded in the field. There are many such phases in engineering, and there are some good reasons for disregarding the exact science of such deductions in field work. A sag table is worked out usually for level country, with a few cases given as exceptions to apply to certain typical points on the line where the profile varies from level. With a line crew out in the mountains under severe stress of weather, working as best they may, possibly at low temperature and with high winds, it is absolutely impossible to get construction men to pay attention to such refinements as are usually given in sag table calculations.

The point of this is that we should not rely too much on theoretical data of this sort. We should give our instructions in such form and should make our designs with sufficient margin so that results can come within the scope of action of the average construction crew, and not make the operating success of a transmission line dependent upon the fulfilment of all of the exact theory exemplified in a sag table.

F. W. Peek, Jr.: It requires a certain energy concentration to rupture insulation, break down insulators, etc. Such energy concentration may result when sudden changes are made in the stored energy of the system. These sudden changes may result from internal conditions or by energy impressed from external sources, such as lightning. The results during such changes are called transients. In modern High-voltage engineering the term "transient" has become a common and important word.

In order that energy may be transmitted from one point to another point to be utilized as useful work, energy must be stored in the space surrounding the conductors, in two forms—dielectric and magnetic. Energy is stored in the dielectric circuit with increasing voltage and delivered back with decreasing voltage. Energy is stored in the magnetic circuit with increasing current and delivered back with decreasing current. With transients, as with all electrical phenomena, there are three constants with which the engineer must deal: with resistance, which causes the absorption of energy somewhat analogous to friction; with capacity and inductance, which act as energy storage reservoirs.

The energy stored in the magnetic field is

$$\frac{i^2 L}{2}$$

The energy stored in the dielectric field is

$$\frac{e^2 C}{2}$$

When the current is zero, all of the energy is stored in the dielectric.

If i is suddenly changed, after a given time the circuit gradually assumes a new e and i. The transient occurs between the initial and final values of i. During this time energy is transferred from one form to another at a given definite frequency called the natural period of the circuit:

$$f = \frac{1}{4\pi\sqrt{LC}}$$

The resistance of the circuit acts as a damper and gradually dissipates this energy.

For example: suppose a switch is suddenly opened when all of the energy is stored magnetically. i is suddenly reduced to zero. The energy must be changed to dielectric energy or the voltage must first be increased to a sufficient extent to store this energy in the capacity; thus e becomes

$$\frac{e^2 C}{2} = \frac{e^2 L}{2}$$

$$e = i\sqrt{\frac{L}{C}} = i Z'$$

The term $\sqrt{\frac{L}{C}}$ thus acts somewhat as in impedance and for this reason is called "surge impedance." When energy changes from one form to another in this way at regular time intervals and no energy is transferred along the circuit, it is called a "free oscillation." The oscillation continues until the energy is dissipated by the resistance.

When an oscillation is impressed upon a circuit which has no definite relation to its natural period, it is called a "forced oscillation."

If electrical energy from some external source—such as lightning—is suddenly impressed upon a transmission circuit, it travels along the circuit with the velocity of light and it is called a "traveling wave." The energy stored magnetically is equal to the energy stored dielectrically. The traveling wave may thus be thought of as being made up of a voltage wave and a current wave in phase.

In a standing wave the voltage and current are at 90 deg. (and not in phase as in the traveling wave), as in this case no energy transfer takes place.

These various transient phenomena are all subject, to a certain extent, to calculation, but experimental work is necessary to

determine their cause and the means for their suppressio
The effects may be quite different, depending upon the apparatu
For instance, low-voltage high-frequency forced oscillations ma
be impressed upon a circuit without damage, except in certain a
paratus containing inductance and capacity, where very high loc
over-voltages may be built up. A single impulse of very stee
wave front may be applied to an insulator. The voltage of th
impulse may be many times the 60-cycle puncture voltage of th
insulator. Flash-over results. During the flash-over, whic
requires a very small but definite time to start, this insulator
strained and small local cracks may result. A sufficient numb
of these impulses will cause breakdown of the insulation.
two gaps of differently shaped electrodes are spaced so
to spark over at 100 kv. at 60 cycles, and these gaps are the
placed in parallel and an impulse of steep wave front is applie
discharge will take place across one gap and not the other, eve
though the non-sparking gap is greatly decreased in length. Th
voltage is high enough to spark over either gap. It therefo
goes over the gap requiring the least time to rupture. It may b
interesting to note that a traveling wave 1000 ft. (305 m.) lor
passes a given point on a transmission line in approximately o
millionth of a second. It can be seen that the experimental prol
lem is a difficult one.

From the protection standpoint, oscillations must be absorbe
and dissipated by resistance or the wave front of traveling wav
modified by the two other circuit constants.

Spectacular " high-frequency " tests blindly made on appar
tus are barbarous. Tests of this sort should never be mad
unles thoroughly understood. Rupture does not take plac
at a lower voltage at high frequency (where heating does n
result) but generally a higher voltage is required to accomplis
the same destruction in the limited time. Damage results fro
the enormous local concentration of voltage.

Certain phenomena which always exist go unnoticed in e
gineering until the energy involved becomes great enough t
make them problems. The turning-point may be quite sudde
and it often appears as if new and mysterious factors ente
Such, in a way, was the case of corona on transmission line
Up to 80,000 volts or so the conductors were sufficiently larg
so that dielectric flux concentration was not great enough t
cause rupture. In order to keep the same amount of copper an
transmit greater energy, the voltages were increased. Th
increase of voltage was just sufficient to bring the dielectr
flux density past the rupturing point. Corona phenomen
changed from those of a few brush discharges at rough points o
the conductors to complete breakdown of the air around the co
ductors. Corona thus became a problem, and the laws of coron
loss were determined. A similar turning-point has just bec
passed in solid insulation. The insulation problem has change
from a mechanical problem to a problem of the dielectric circui

Charles E. Waddell: I am inclined to think a right-of-way easement is to be preferred to ownership in fee. Usually an easement is cheaper to acquire; and when containing a proviso for ample clearing of timber an easement will serve every purpose. The length of the span determines the width for timber clearance, and while the right-of-way strip may itself be of inconsiderable width it may be very necessary to clear high standing timber to quite a distance from the line, as high winds frequently blow the line far out of plane.

As to the question of grounded steel towers versus wooden supports, I confess that at the present state of the art I am leaning back toward wooden pole construction with wooden arms and non-grounded fittings. I have in mind a line where a steel tower line is paralleled by a wooden pole line, both 60,000 volts, from the same transformers. The wooden pole line is of standard, conventional crossarm construction, with pin type insulators. The steel tower line is equipped with suspension insulators. The interruptions on the suspension insulator line have been too numerous to count, while the wooden pole line has yet to have its first interruption.

A point brought out by Mr. Buck is the question of line ballasting and the effect of swinging of insulators. It seems to me that it is desirable to suspend the insulators so that they have infinite latitude to swing with the line, making a hinge for that purpose, but that the movements across the line be restricted to the lost motion in the joints themselves. With a wind blowing across the line, the swinging is restricted to the individual span, —the line as a whole is not deflected outward. This prevents a wave starting that may ultimately end in the line rotating, with the result in some cases of wrapping the conductor around the ground wire.

I heartily agree with Mr. Buck as to the wisdom of using a number of small, single-piece, inexpensive disk insulators. I believe these are to be preferred to the use of the two-part insulator with its greater surface and greater first cost.

I cannot say that I agree with Mr. Buck on the subject of ballasting the line, however. It seems to me it might be a very excellent desideratum where some emergency condition had to be met, but in designing new work I think that a lower voltage and larger wire, a more carefully graded line, and closer tower or pole spacing, would meet the same ends without introducing the added weight on structures and stresses on the insulators.

Reference was made in Mr. Brundige's paper to the fatigue of porcelain. I want to suggest that this fatigue, perhaps, is not due alone to the electrical stresses, but to a combination of electrical and mechanical stresses. The majority of insulators strung up and sustaining only their own weight successfully withstand laboratory test for flash-over and puncture. The same strings of insulators when placed on the line and supporting the weight of the conductor, which may be 1000 lb. (453 kg.) or

more, break down under a very slight rise in voltage. The only conclusion I have been able to reach in the matter is, that, due to some obscure phenomenon, the dielectric strength of the insulators is weakened, and that if the mechanical stresses were removed the insulation would in all probability be as high as when actually tested.

Of the types of conductor mentioned in the committee's report, the one that particularly appeals to me is the steel-cored aluminum. I built an experimental line of this material in 1910. The line was seven miles (11.3 km.) long and of three conductors, equivalent in carrying capacity to No. 0 copper. The wire had a breaking stress, I believe, of some 6000 lb. (2720 kg.), and an elastic limit of some 4000 lb. (1815 kg.). The cables were drawn with a dynamometer to about one-fourth the ultimate strength; approximately 1500 lb. (680 kg.) The topography of this particular line indicated that some such conductor was best suited to the particular need. The spans varied from approximately 200 ft. to 2400 ft. (61 to 730 m.).

I have had this line under critical and constant observation since it was built, and have no fault to find with it whatever. Due to bad judgment on my part, the wires were placed too close together, and the high winds have occasionally swung them together; and when the burn is sufficient to fuse the aluminum, it is found that the steel core sustains the strain, and further, that the aluminum under the stress unwraps and frays, making it easy to locate the place by observation from the ground.

Another reason for using it, a reason which I think is a good one, is that, assuming the life of the cable is short, say twenty years for example, the saving over the cost of copper for such a line is ten per cent to fifteen per cent; and if the line is completely destroyed within the twenty years, the material has justified its use.

Percy H. Thomas: The most important topic brought up, it seems to me, is the matter of the so-called deterioration of porcelain. It has developed to a critical point during the last year in many different parts of the country and with many different kinds and makes of insulators. The deterioration has developed, sometimes, where it could not possibly be due to electrical causes; and sometimes it is an open question whether it is not due to electrical causes. The problem is to find out what it is, and how to overcome it.

I think we can conclude that it is not due to the deterioration of porcelain *per se*, for, taking the worst cases of breakdown of insulators, there are many insulators which are, apparently, absolutely uninjured, and moreover, in any which are injured, much material is good. It is, in my opinion, therefore not a deterioration of the porcelain *per se*. It is, further, not always due to the presence of electrical potential. I think that in all probability a great deal of the deterioration is due to things that happen during the processes of manufacture. When you remember that the material at one time is in a plastic state,

and that when it is burned it has to shrink into a semi-crystalline mass, keeping every portion intact, you can see that, during the forming, the pressing and the twisting it gets, somewhere on the interior there may very readily occur a slight plane of weakness or an actual separation. The edges may be daubed over and adhere, yet this fault will never be corrected. There may be enough good porcelain to hold the potential during the test, while the insulator is new, before the faults develop, but after repeated heating and cooling or strains produced by expansion of other parts, there may be further development of the mechanical fault. I think the evidence of the general situation points to this conclusion.

You cannot exactly blame the manufacturers for it, as they are doing the best they can, and there is no one manufacturer who has all the trouble. It is a problem which we must work out with time, and meanwhile we must find some way of detecting the bad insulators. That can partly be done by tests, but we need a few new tests.

If we can assume that the difficulties in high-tension insulators are, most of them, due to defects depending upon the history of the individual insulator, that immediately puts a premium on the two-piece insulator with two shells independently made, and put together. For if one shell is defective there will not be, in all probability, another defective shell along with the first. But with the two-piece insulator the flash-over voltage should be so low that a single piece of porcelain will be sufficient to withstand the full strain and prevent a puncture. If reliance is placed on one shell when the other is injured, that shell alone must be able to take care of the flash-over. This double-piece insulator has a great advantage, considering incidental mechanical strains, in that, if due to expansion, or heavy stress, there is a small check on the inner petticoat, due to mechanical reasons, there still remains the outer shell intact. The mechanical strains on the outer shell are far less, on account of the larger dimensions.

R. J. McClelland: As to tower specifications, I am thoroughly in agreement that in all tower calculations the figured ultimate strength of the structure should be determined by the elastic limit of the steel; also that at least one of each type of tower should be tested to failure and the working loads for which the tower is to be used checked against the actual ultimate strength.

With regard to the term " factor of safety," I am of the opinion that the use of this term as applied to a transmission line tower, as a whole structure, is misleading and should be abandoned, and that the term " margin of safety " should be adopted in its stead. The term " factor of safety " should be used then only with reference to the unit stresses of the individual members of the structure.

The term " margin of safety " indicates the relative excess strength of the built-up structure, and has no direct relation to the unit stresses in the members.

When writing specifications for towers one should consider the specified test loads as being practically the ultimate strength of the structure. The working loads should then be specified with an ample margin of safety, and these working loads should be put in the specifications for field use, instead of the test loads. In this way, the tendency of the construction men to consider the tower good for all loads that do not exceed test loads will be avoided.

With regard to tower footings, it would be valuable to receive data from various engineers as to the comparison of steel footings in earth with similar footings encased in concrete. In some earths and localities a standard type of concrete footing can be installed as cheaply as a safe earth footing and gives much better construction, while in other situations the earth footing is amply safe and much cheaper. In the case of towers with concrete footings, I consider it well to make a substantial earth connection. This is a feature that has been neglected on many of the earlier lines.

It would be valuable to possess reliable data on the action of alkaline soils on steel or concrete tower footings and on the effectiveness of concrete waterproofing methods, either integral or external, in preventing this action. When earth footings are used in acid or alkali soils, we would recommend protection of the stubs either by the application of coal tar or other suitable paint for perhaps two feet (60 cm.) below and one foot (30 cm.) above ground level, or by a concrete sleeve cast in a hinged sheet steel or other form, covering the same portion of the steel stub. Both methods leave the towers well grounded through the steel grillage of stubs and provide additional protection at the point where corrosion is likely to be most active.

Taking up the question of the arrangement of conductors, with regard to the "staggering" of conductors in vertical arrangement, it would be interesting to learn from the engineers who have used the extended middle arm construction if this has given the desired freedom from "sleet jump" troubles. Has it been proved that 2 to 3 ft. (60 to 91 cm.) horizontal offset in a span of over 1000 ft. (305 m.) gives satisfactory operating conditions at voltages of 60 kv. and over?

For protection against severe wind conditions only, the vertical arrangement of conductors is the better, whereas the horizontal arrangement of conductors is better for protection against sleet troubles.

In some recent 110-kv. construction, an interesting expedient has been used to guard against excessive sag produced in one span due to unequal distribution of sleet over the adjacent spans. At every third or fourth suspension tower a special "semi-tension" insulator construction is used; that is, instead of one single string of insulators in suspension which allows the conductor to move in the direction of the line, as much as 14 in. (35 cm.) in the case of extreme uneven sleet load, two strings have been

used, attached to the tower at an angle of 45 deg. like an inverted V. Under normal conditions a tower with this construction is practically a suspension tower, and the conductor runs straight through without a sudden change in direction, such as occurs at a tower equipped with tension insulators and a jumper; but whenever unequal sleet loading takes place, the tendency of the heavily loaded span is to rob the adjacent spans of their sag, and this is opposed by one of the " semi-tension " strings acting more as a tension insulator. I understand that sand-bag loading tests have indicated this construction to be effective and the application of this idea might prove of benefit for existing lines in the heavy sleet territories. This installation will be watched with interest.

It may be noted that I have used the term " tension insulator " in place of the usual " strain insulator," as the former designation would seem more closely descriptive of the actual working conditions of the insulator.

As to railroad and telephone crossings, during the past year we have installed a modified type of crossing protection on our lines in various parts of the country, that has met with the approval of the railroads and the signal companies. This construction consists of two parallel strings of standard suspension insulators spaced 15 in. (38 cm.) apart in the direction of the line, suspended from the ends of a Z bar rigidly secured at right angles to the axis of the crossarm, and the suspension clamps positively spaced at the conductor end by a malleable cast iron bar; the latter serves as the clamping piece in both suspension clamps, and has projecting ends which act as arcing tips. Standard towers designed for use with either suspension or tension insulators are used at each end of the crossing span, this span being somewhat reduced in length compared with the normal span. The main considerations leading to the adoption of this construction were as follows:

(1) That of increasing the safety of the crossing span by the use of an extra string of suspension insulators to support the conductor in case of mechanical failure of one string.

(2) The elimination of tension insulators, which, in our opinion, do not increase the safety of the crossing span as regards the falling of conductor, and are, moreover an extra hazard to the operation of the line.

(3) The desire to obtain satisfactory results without going into elaborate constructions, which in themselves are frequently more of a hazard than otherwise.

It is the experience of our companies that a large proportion of troubles originates from insulator failures rather than from mechanical failure of the conductors, and in this double suspension construction we have worked on the principle of increasing the margin of safety in the insulators supporting the conductor.

With the rapid advance into higher transmission voltage the present crossing specifications providing the same construction for all voltages of 5000 or over have become inadequate

to meet all the conditions involved, and in order to cover logically the wide range embraced there seems to be a distinct demand for subdividing into at least two classes, perhaps at about 15,000 volts. This would require a separate complete specification embodying simpler, but effective, types of construction for the lower or distributing voltages, and another specification suitable for the higher or transmission voltages.

Concerning transmission line hardware, for all heavy service I have found it desirable to eliminate malleable cast iron hardware, and it would be well if structural or pressed steel fittings, or mild steel castings, were developed for this service, on account of the increased reliability that would be obtained thereby.

On certain recent double-circuit tower line construction our company has equipped both suspension and tension clamps of all insulator strings of one circuit with discharge horns, leaving the other circuit with discharge horns on tension clamps only. It will be interesting to compare the performance of these two circuits in service.

V. Karapetoff: I wish to take exception to the statement No. 5, in Mr. Buck's paper, where he says, " Draw the conductor up tight throughout the line. A too conservative allowance of slack to guard against possible mechanical stresses in the conductor will cause more trouble than it will prevent." I am afraid this statement, coming from such an authority as Mr. Buck, will cause us more trouble than it will prevent. Several cases came to my attention not long ago where considerable trouble was caused by the conductor being drawn too tight, without reference to the stresses in the winter or during high winds. By interviewing the line superintendents, I found out that it is difficult to force the construction gangs and the foreman to conform to the tables of sags and also to use the dynamometer where the sag is determined by sighting the line. I wish very much that Mr. Buck would modify his statement so as to remove the impression that he does not believe at all in the correct calculation of sags and stresses, but simply advises us to draw up the lines as tight as possible.

P. M. Lincoln: Mr. Faccioli does not approve of switching on the high-tension sides of lines. Personally, I must say that I do not agree entirely with that position. Practically, I have never seen any bad effects from switching on the high-tension side, and theoretically I have always taken this position, namely, that although I am ready to admit that switching on the high-tension side does give rise to surges, these surges which it gives rise to are so small, compared to the surges which come from other operations, particularly from lightning, that if the apparatus is not capable of withstanding all the surges which arise from high-tension switching it surely will not stand the surges which arise from lightning.

I would like to make a statement in regard to the point just raised by Mr. Karapetoff. I am inclined to believe that Mr.

Buck is quite correct in the way he puts it. I do not believe that any great difficulties are to be anticipated from drawing lines too tight. I think the tendency is in the other direction—to allow them to become too loose. If a line is put up too tight and cold weather comes along, it may possibly strain the material of the line above the elastic limit, but what is going to happen if it does? It simply stretches a little, and when the warm weather comes along the stretch will result in a little more sag than before, but to stretch the material of the line above the elastic limit is not necessarily going to hurt the material. The material, in the course of its manufacture, has been strained above its elastic limit continuously, and if it is strained above the elastic limit after it is in service it is not by any means fatal to the line.

Farley Osgood: I think the manufacturers of our various lines of materials are doing about all that can be expected of them in the way of investigation for improvement. I do not think that the operating engineers, as a whole, are doing their share of investigating work. I think that it is up to the operating engineers to plan to spend sufficient money for proper testing schemes and devices, in order to help the manufacturers and designing engineers in the field, so that they can test in actual practise.

A point which has brought this matter vividly to my mind within the year has been our own considerable expenditure toward the investigation of the effect of high frequencies on the insulators and lines, and we found that insulators which had behaved reasonably well, as we thought, broke down very quickly under our high-frequency test.

Mr. Faccioli brought out clearly that the difficulties from voltage can be reasonably well cared for, and the difficulties from short circuits can be reasonably well cared for, particularly by means of reactance, but I do not agree with him at all that we should keep away from frequent switching. It cannot be done, in a complicated, busy territory. In our large power stations, with a heavy service, we will switch, for one cause and another, twenty to sixty times a day. It cannot be stopped. It has to be done. The engineers have to meet these conditions. I entirely agree with Mr. Lincoln that if the apparatus will not meet the service requirements it must be made to.

In my opinion, the difficulties from high frequencies are not well enough understood. The reason they have not been given careful study previously is because we have been so busy eliminating the difficulties from short circuits, high pressures, etc. Having cared for these, we can now take up the study of the effects of high frequencies. If we had done this before, many of our present difficulties would not have been known to us.

J. A. Sandford, Jr.: Mr. Brundige has suggested that engineers put into every insulator specification a description of the materials to be used. I do not believe that is a possibility. I had occasion to look up not long ago the chemical analysis

as laid down for what we call ball clay, or kaolin, from Kentucky, North Carolina, Georgia, one or two places in England, and one in France. You could lay these in a row here on this table and label them, and then take the labels off, and change them around, and you would never know which applied to which, they are so nearly the same. The great difference between the various clays used seems to be in their plasticity, but no one can tell what plasticity is or what causes it. Therefore, I think Mr. Brundige's suggestion would prove impracticable, particularly at the present time, with our limited knowledge of such things.

Second, on the question of fatigue of porcelain. I think that if a piece of porcelain is absolutely vitrified there is absolutely no fatigue. To my mind, what has been called fatigue of porcelain is simply the gradual giving way of porcelain that, in the first place, was not perfect, either through flaws, or from the vitrification standpoint.

To refer to a different matter, I think that a large percentage of the insulator failures on transmission lines would have been eliminated if, every time the patrolman went out to change an insulator—this has reference particularly to suspension type insulator lines—he had taken down the complete string of insulators and substituted a complete string of new insulators which he was sure were good. If you go out and look at a string of insulators on which you know there is trouble, there may be two or three disks that you can see are no good, and there may be two or three that look as if they are all right, and they may or may not be so.

There is one point Mr. Sothman brought up today, which was referred to here last winter, which I would mention again now, and that is the desirability of having at some place or other a laboratory where just and accurate comparative work on insulators and other similar devices can be done. The insulator manufacturers have done, as some one has said, about all they can do. It seems to me if the plan of having such a central testing laboratory could be carried out, either with or without the sanction of the Institute, it would be a great thing.

E. R. Albrecht: I notice in Mr. Sothman's paper, "Problems of High-Tension Transmission Lines," the following statement, relative to the crossing of high-tension lines—"There is at present no generally recognized type of crossing protection."

Did not the High-Tension Committee of 1911, together with the committee appointed by the National Electric Light Association, the American Electric Railway Association, and the Association of Railway Telegraph Superintendents, prepare Specifications for Overhead Crossings of Electric Light and Power Lines, which were accepted by the various associations?

Have these specifications still the approval of the Institute? Do they not cover the recognized type of crossing protection? If they do, why did not Mr. Sothman mention them? If not, what parts should be superseded, and by what?

The installation of proper crossing protection constitutes a part of my duties, and I am very much interested to know just how the Institute as a whole regards the specifications mentioned, and also, if the present High-Tension Committee recommend their use, and if not, whether they have any plans for revising them.

William L. Puffer: I am very much interested in what has been said concerning the life, deterioration of and failure of the several types of insulators in common use, because of an investigation of mine into the cause of undue leakage over the busbar cell-work and insulations of a moderately high tension station.

In this station it was known that there was some kind of ground or similar trouble, because at times tiny sparks had been noted at the heads of bolts and washers used in assembling the insulating slabs, and several disagreeable shocks had been received by attendants. As soon as possible a section was cut out of service and the parts dismantled, and to my surprise there was found a large collection of wet green paste on the copper bolts and studs. Chemical examination proved the presence of nitric acid, water, nitrate of copper and several sub-nitrates. The surface of the porcelains and all pores and cracks were wet with nitric acid of sufficient strength to destroy organic washers that had been used to distribute the pressure between the porcelain and the clamping nuts and bolts.

Further examination proved the presence of nitric acid in the cracks of both wet and dry process porcelain bushings, on the surface of the insulating coverings of the busbar cables and on the porcelain bushings used to support the cables where they passed through walls and barrier.

I was able to prove that all of the trouble originated in the small air spaces where the potential gradient was high enough to produce light and minute sparks of the type called " static ". First there was produced ozone, then nitric acid and then action on the copper with the formation of nitrates. Similar action was found about some iron washers and bolts used in the construction of switches and the switchboard.

These results were not a matter of conjecture but of actual chemical proof obtained while the parts were alive and carrying current, and it certainly suggests that if a 6600-13,200-volt system can be subject to as great action as I found, there is ample room for thought as to what must be the conditions around the insulating parts of the highest tension lines now in use.

Whenever and wherever an insulating support shows a glow with little sparks in it there is likely to be the formation of ozone, and if a little moisture is present there will next be nitric acid. The wind may blow it all away, or a porous porcelain may slowly absorb it, with gradually lessening resistance, leading finally to a puncture and a short-circuit.

Ernest V. Pannell: Mr. Sothman's suggestion as to the establishment of constants to cover the commercial properties

of aluminum and copper is one well worth acting upon, and it would afford the manufacturer some idea of what he would have to work on and would give the engineer figures upon which to base his calculations. At present there is no recognized standard for these properties, and specifications are different all along. In particular reference to aluminum, the specification of elastic limit should have some reference to the size of the wire, as I have found on test that the elastic limit varies from 10,000 up to 20,000 with decrease in the gage. The new German rules, it is interesting to note, do not specify elastic limit for conductor material, but only elasticity, and give a maximum figure of 10,000 lb. per square inch for the stress in aluminum. This latter practise is to be deprecated, as it does not offer the same encouragement to the manufacturer to produce material of extra high grade as when the working tension is specified at so much per cent on the elastic limit.

Of methods and charts for determining tension and sag we have had rather a plethora, and if the Institute were to standardize one set of curves for both copper and aluminum, the result would be worth the trouble expended. The *Verein Deutscher Elektrotechniker* went into this subject very thoroughly last year and their recently published hand-book of standards for overhead lines is a model of conciseness.

Regarding steel reinforcement for aluminum cables, the British manufacturers do not view this practise with disfavor so much as being an unnecessary innovation. We can point to spans in Europe of 700 ft. (213 m.) and up to 2000 ft. (610 m.) being run by aluminum without steel centers, so there does not appear to be any crying need for reinforcement where the highest possible grade of aluminum is used. A composite cable made up of two materials, one of which has three times the specific extension of the other, seems to add just a little unnecessary complexity.

Julian C. Smith: I think operating men who have had experience in operating transmission lines of 50,000 volts and upwards, with pin type insulators, realize there has been a decided deterioration in the pin type insulators. The fact that it is easier to find the deterioration in the suspension type insulator, easier to replace the defective parts, would by no means indicate that the suspension type, *per se*, is any worse than the pin type. This is the more evident when you consider that practically all suspension type insulators are operating with one end grounded, whereas a relatively small number of pin type insulators subjected to the same voltage, are operating under these conditions.

There is one point in Mr. Buck's paper to which I take exception, and that is the number of units which would be put on very important transmission lines. It seems to me that the number of units should be fixed by the climatic conditions or local conditions rather than the operating voltage.

E. A. Lof: Mr. Sothman suggested that the clearance between the transmission wires and the ground should be in a cer-

tain relation to the transmission voltage. So far as I can see, this has nothing to do with the voltage, whether it is 50,000 or 150,000 volts. We must string the wires high enough to protect human life and to allow certain vehicles to pass underneath.

I would like to get Mr. Sothman's views on the necessity of grounding steel towers when provided with concrete foundations, and his views on the mounting of grounded wires on wooden poles. If the ground wire is not grounded at every pole, should it be supported on an insulator there, and if so, for what voltage should it be insulated?

C. O. Mailloux: One of our distinguished members, Cavv. Ing. Guido Semenza, of Milan, Local Honorary Secretary of the A. I. E. E. for Italy, has recently published a comprehensive set of charts containing in graphical form all the information needed for running overhead lines; *i.e.*, giving the sags and stresses that occur in overhead conductors of different sizes, in spans of different lengths, at all temperatures, and under all conditions of extra loading due to ice and wind. By means of these charts all determinations of sags and stresses for any set of conditions can be made in most simple manner by the man in charge of the work of constructing the line. It is probable that an English edition of this work will be brought out before long.

E. M. Hewlett: Mr. Buck has explained that if an insulator is designed with a petticoat so short that the flash-over point is much lower than the puncture point, normally, under both dry and wet conditions, the insulator will be less severely strained and will not be subject to as rapid deterioration as has been shown by some of the insulators used now. A number of the recent insulators have too great a diameter of petticoat, so the flash-over is too close to the puncture voltage.

Then, again, if you insulate your line for lightning conditions, as suggested by one of the last speakers, it will also be necessary to protect or insulate the transformers, lightning arresters, switches and everything else for the same conditions. This is a most important consideration.

Also, in the matter of mechanical strength, the distortion in design of the insulator to give great strength often works against the electrical characteristics. You thus handicap yourself when you ask for strength greater than is required.

In reference to the fatigue of porcelain, I have not seen the proof that well-vitrified porcelain undergoes fatigue, unless overstrained. From anything we have seen so far, I believe that what is known as fatiguing is largely the result of flaw of some description or of incomplete vitrification. That is, when not properly vitrified, the insulators will eventually absorb moisture. The glaze will protect the insulator for a time, but gradually deteriorates and then absorption through the porcelain begins and the unbaked porcelain gradually absorbs moisture and breaks down.

H. W. Buck: I am glad that Dr. Karapetoff has raised the question covered by Paragraph 5 in the conclusions at the end

of my paper, for it offers an opportuntity to accentuate the point which I desired to cover in this paragraph. Most transmission lines are too slack, and during the past year reports have come in from all parts of the country giving instances of short circuits resulting from conductors swinging together under wind stress, even where liberal clearances were allowed between conductors.

It has become customary to assume a heavy loading of sleet and the simultaneous action of wind velocities up to 100 miles (161 km.) per hour, allowing slack for these conditions, and then in addition to throw in a little for good luck. On top of all this slack, after the line has been in service for a few months the natural stretch which takes place in all conductor materials before a condition of permanent set has been established, still further increases the sag of the spans. The result of this is that many transmission lines are a series of festoons between tower supports, with all the lack of inherent stability which such a condition gives rise to.

I cannot see any reason for modifying this statement in regard to drawing the wires up tight, unless by supplementing it with a statement that the towers must be made strong enough to withstand the strain. The first line of the paragraph in question should of course be read in connection with the following three lines, which qualify it, I believe, sufficiently.

K. C. Randall: Mr. Rushmore has pointed out that insulators have not been developed along the lines of exact science

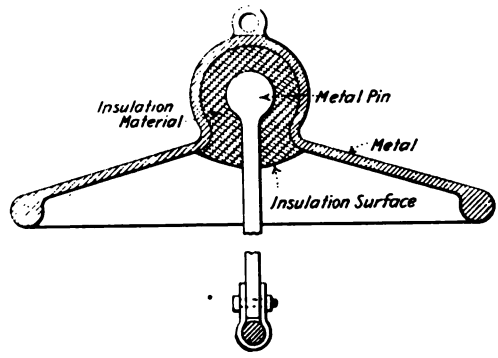

FIG. 1

like other pieces of electrical apparatus. This comment seems to be well founded so far as the average commercial insulator is concerned.

During the past five years considerable investigation on the proper design of insulation has been carried on, in the course of which the influence of shape as well as dimensions has been better understood. As a striking illustration of this, the In-

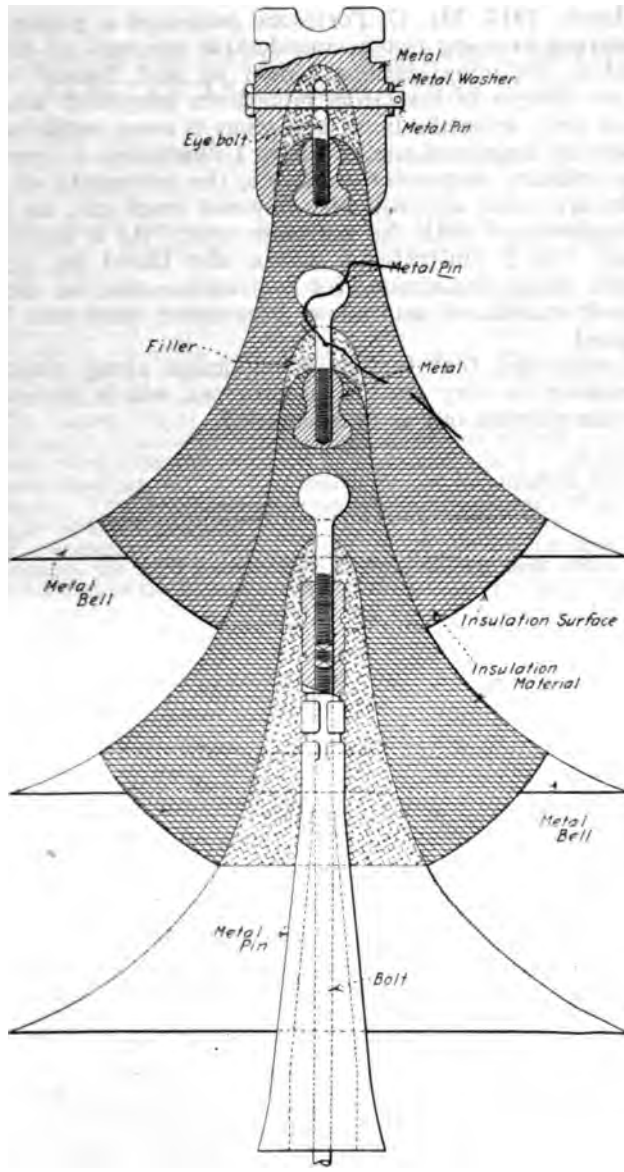
Metal
Metal Washer
Metal Pin
Eye bolt
Metal Pin
Filler
Metal
Metal Bell
Insulation Surface
Insulation Material
Metal Bell
Metal Pin
Bolt

FIG. 2

stitute is considering the standardization of a spherical or ball gap, because of its dependability, as a successor to the previous needle gap, so notoriously variable.

In March, 1913, Mr. C. Fortescue presented a paper before the Institute bringing out a considerable amount of the data obtained in the investigations I refer to, and, based on such data, two designs of insulators have been proposed which are based on truly scientific lines, and what is more striking, they are made up largely of metal. Fig. 1 illustrates a type quite like the ordinary suspension insulator, the petticoats of which, however, are metal and will certainly not crack off, as is commonly experienced with the porcelain type. As a form of pin insulator, Fig. 2 illustrates a design also based on scientific principles, whose dimensions for any service can be definitely and closely calculated, and whose breakdown tests can be predetermined.

It is suggested that further development along these lines will probably be very fruitful of progress, which today's discussion has pointed out as much needed.

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THE ECONOMICAL CAPACITY OF A COMBINED HYDRO-ELECTRIC AND STEAM POWER PLANT

BY CARY T. HUTCHINSON

ABSTRACT OF PAPER

This paper develops a general method for determining the economical capacity of a combined steam and hydroelectric development.

The method involves the use of two curves—one, the "Percent-Deficiency," giving the stream regimen, the other, the "Percent-Load," giving the characteristics of the load. The first curve gives the percent-deficiency of the water for any stream-flow, and hence fixes directly the deficiency in energy which must be made up by the steam plant. The second curve shows directly the proportion of the total energy of the load that is included above any proportional part of the maximum power, and fixes the capacity of the steam plant required to supply that part of the load which cannot be supplied by the stream. The use of these two curves differs for plants with pondage or without pondage.

The capacity and output of the steam plant being thus determined, its total annual cost is determinable and with the annual cost of the hydroelectric plant, fixes the total annual cost of the combined plant. This is done for the range of stream-flow by means of numerical examples.

INTRODUCTORY

IT IS the object of this paper to outline a method of determining the point of economical capacity of a hydroelectric plant on a variable stream, when developed in connection with an auxiliary steam plant to supplement the deficiencies of the water supply. This question arises whenever a hydroelectric development is undertaken, and many ways of answering it are current; but they are practically all engineer's guesses, or are "cut-and-try" methods. As far as I know no direct method of handling the problem has been pointed out.*

The question presents itself in two forms: First, in the case of a proposed new development on a variable stream, for what

*Since the presentation of this paper, my attention has been called to the fact that Dr. Adolf Ludin had previously treated this general subject in a similar manner in his book entitled, "Der Ausbau der Niederdruck-Wasserkräfte nach wirtschaftlichen Grundsatzen." Dr. Ludin's work forestalls mine by several years and he is entitled to priority in the general manner of handling the subject, but he has not developed the "percent-load curve" with the theorems attached to it, as I do on pages 168—et seq. This is the only novel element in my paper; the remainder is simply a new use of old material, such as the well known "duration" and "deficiency" curves.—C. H. T.

stream-flow shall the development be made? Second, assuming a plant already in operation, to what extent shall an auxiliary supply be provided in order to convert the " variable " supply into a " continuous " supply? Both cases involve a determination of the total annual cost of an auxiliary supply adequate to supplement the deficiency in stream-flow. In one case, the selling price of the combined hydraulic and auxiliary supply is to be determined and the development fixed for such stream flow that at this price the supply can be sold, in the given market. In the second case, the question is the determination of the cost of the auxiliary supply for various degrees of insurance and the comparison of this cost with the additional earnings that can be obtained from the sale of a " continuous " supply as compared with a " variable " supply. The two cases really merge into one, since both involve the determination of the total annual cost of the auxiliary supply, under the prevailing conditions of the power load and for the hydraulic characteristics of the particular stream.

In the case of a new project, the cost to build the hydraulic development per kilowatt is less as its capacity is increased, since a large proportion of the total cost is practically independent of the capacity of the equipment. In this case, an increase in the annual cost per kilowatt of the auxiliary steam plant is accompanied by a decrease in the annual cost of the hydraulic plant, and a point may be reached at which the sum of the two is a minimum. This would fix the most economical capacity of the development and hence the point of greatest profit for a given market price of energy. But it does not follow that it may not be desirable to develop the plant for a greater output, even if the profit per kilowatt is less. The limit to the development will, in all cases, be that at which all profit disappears.

The crux of the matter then is the determination of the cost of the auxiliary supply (hereafter referred to as the " steam " supply, although the argument is the same for any other kind of auxiliary plant) for the hydraulic characteristics of the stream in question, and as applied to the particular conditions of power load prevailing in the market in question. As a solution of this problem, I have devised a new form in which to present the hydraulic characteristics of the stream, which I call the " percent-deficiency " curve, and a new form in which to present the characteristics of the load, which I call the " percent-load " curve. The use of these two curves, the one summarizing the stream-flow data, the other the conditions of the load, makes

the determination of the total cost of the steam supply for any conditions of load, for any particular stream, a simple matter.

It may be worth while to call attention to the many assumptions that are made by engineers and others in the determination of the stream-flow for which a development shall be made. Some of the criteria that have been used are given in Table I, which shows various data of the Susquehanna River at McCall Ferry, for the period of twenty years from 1891 to 1910.

TABLE I.

SUSQUEHANNA RIVER AT MCCALL FERRY FOR 20 YEARS, 1891-1910. DRAINAGE AREA 26,000 SQ. MILES.

Basis of Flow	Sec.-ft.	Relative Flow
1. Lowest day in the period	2,200	1.00
2. Average for lowest week in the period	2,800	1.28
3. Average of the two lowest 7-day periods in each year, for 7 years (1904–1910)	6,300	2.87
4. Average flow for the lowest week of the lowest month of the six highest months for each year of the period (1904–1910)	20,000	9.10
5. Average of annual one-day minima	5,200	2.37
6. Nine-months flow for lowest year	5,400	2.45
7. Six-months flow for lowest year	12,000	5.48
8. Nine-months flow for average year	12,000	5.48
9. Six-months flow for average year	25,000	11.40

The differences in the choice of the basic stream-flow are great, bringing out clearly the fact that they are little more than guesswork; all are obviously deficient, inasmuch as they leave out of consideration the market for power. It needs no argument to prove that where power can be sold at a high price and conditions are favorable, the development can be carried to a higher point of stream-flow than where the opposite conditions prevail. Referring to the Table: No. 1, the absolute minimum, may be called the banker's or layman's criterion; it is this that the engineer is often confronted with, and has to explain away. Nos. 3 and 4 are assumptions of a basis of estimating power by a bureau of the Federal Government; the others are engineer's guesses.

Putting guesses aside, the determination of the question depends upon two principal factors:

1. The hydraulic characteristics of the development, and
2. The characteristics of the power market.

The treatment of the hydraulic problem is different in the case

of (a) hydraulic plants with pondage, and of (b) hydraulic plants without pondage. With pondage, the hydraulic energy during the periods of low stream-flow should be used to supply the peak-load, as far down as possible; on the other hand, without pondage, the hydraulic energy should be used to supply the base-load, during the periods of low stream-flow; in both cases the hydraulic energy is thereby utilized most advantageously.

By pondage is meant only sufficient reservoir capacity to permit using the daily inflow of the stream at any rate of outflow from the water wheels; that is, it assumes regulation of daily load only, and does not extend to weekly or seasonal regulation.

Regimen of the Stream

The fundamental data of stream-flow are usually given in the form of the hydrograph, Fig. 1; the ordinate gives stream flow and the abscissa the days of the year; the area of the curve up to any point gives the total run-off up to that point. From the hydrograph, Fig. 1, is deduced in the usual way, the " Duration " curve, Fig. 4, giving the different values of stream-flow from Fig. 1 arranged in order of magnitude, without regard to calendar order; the resulting curve shows the number of days in the year, regardless of order, for which the stream-flow does not exceed any particular value.

Fig. 1 gives the hydrograph for the Susquehanna for the year 1896, which chances to represent very closely the average regimen of the 20 years, 1891-1910. Fig. 2 gives for the same year, the low discharges, such as would be useful for a power-development; all flows greater than 1.0 sec-ft. per sq. mi. are omitted from this figure. Fig. 3 gives the low discharges for 1909, the lowest year; from these hydrographs the duration curves of Fig. 4 for the years 1909 and 1896 are deduced.

The duration curves of Fig. 4 are very irregular and are of little use in this particular form. If the curve for a certain year must be used, a smooth curve should be drawn representing as closely as may be the stepped curve of Fig. 4. The inherent uncertainty in gage readings and measurements of stream-flow makes it probable that a smooth curve drawn through the points will represent the actual conditions fully as well as the stepped curve itself.

The duration curves of Fig. 4 as well as all the hydrographs used as illustrations are for the Susquehanna at McCall Ferry where the drainage area is approximately 26,000 sq. mi. The stream-flow has in all cases been reduced to flow per sq. mi.

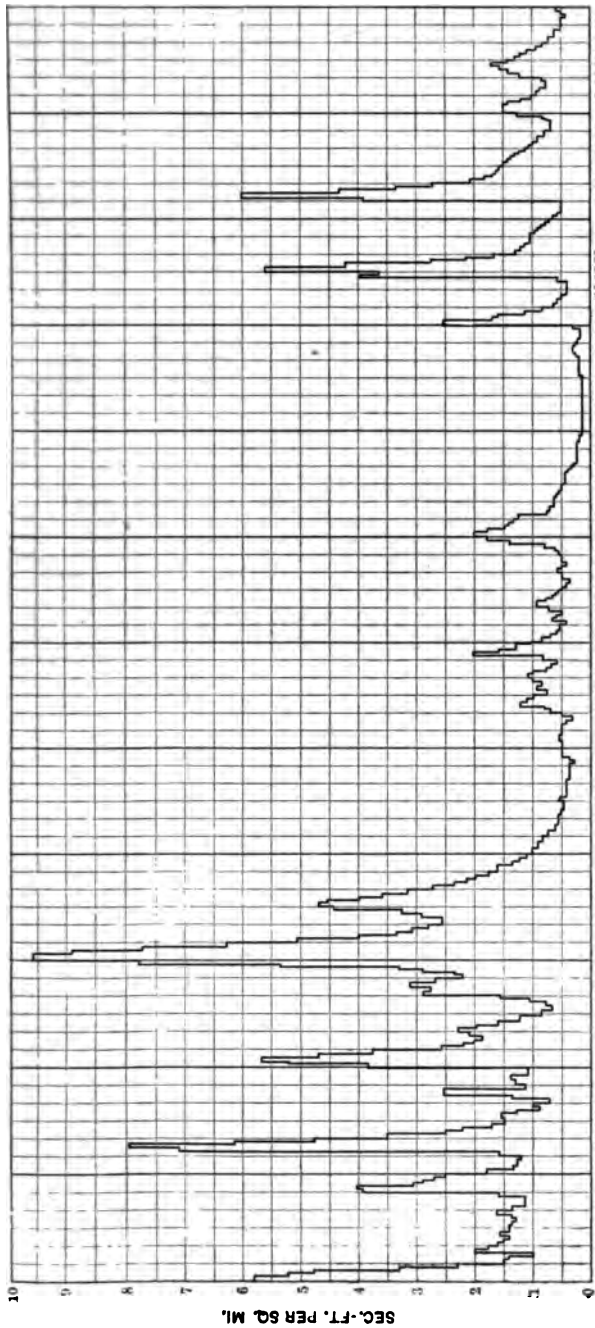

FIG. 1—HYDROGRAPH OF SUSQUEHANNA RIVER AT MCCALL FERRY FOR THE YEAR 1896, REPRESENTING THE AVERAGE YEAR. DRAINAGE AREA, 26,000 SQUARE MILES.

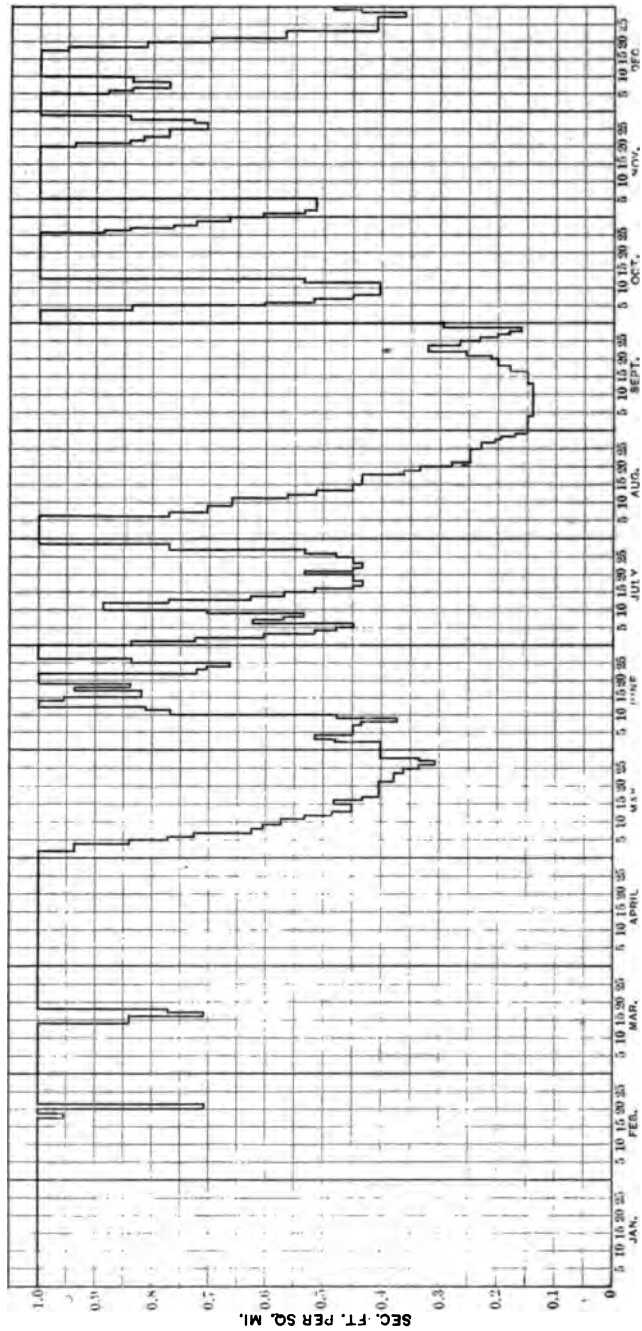

FIG. 2—HYDROGRAPH OF SUSQUEHANNA RIVER AT MCCALL FERRY FOR THE YEAR 1896, THE AVERAGE YEAR, FOR STREAM FLOW UP TO 1 SEC-FT. PER SQUARE MILE ONLY. DRAINAGE AREA 26,000 SQUARE MILES.

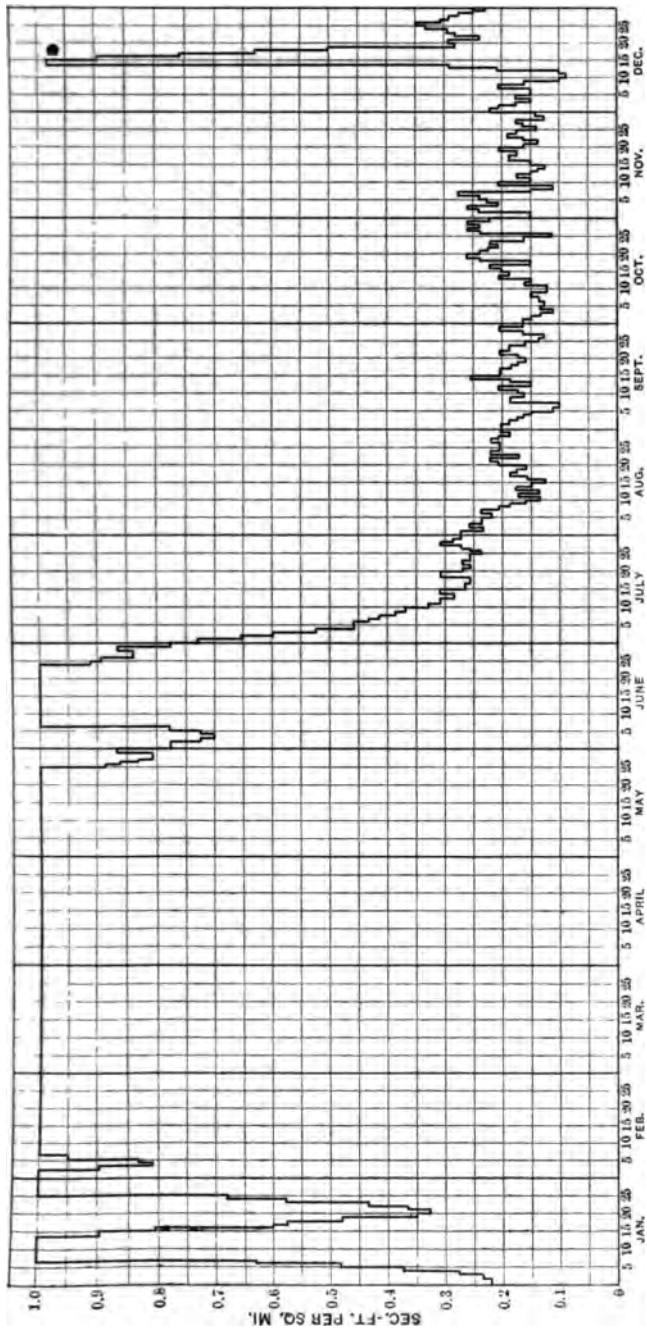

FIG. 3—HYDROGRAPH OF SUSQUEHANNA RIVER AT MCCALL FERRY FOR THE YEAR 1909, THE LOWEST YEAR, FOR STREAM FLOW UP TO 1 SEC-FT. PER SQUARE MILE ONLY. DRAINAGE AREA 26,000 SQUARE MILES.

This is done for the sake of greater generality and to make easier comparisons with other streams. It should be understood in what follows that the specific flow is in all cases to be multiplied by 26,000 to get the discharge at the point in question.

The average duration curve for the 20-year period is given in Fig. 6. The curve is drawn to follow the points quite closely and is somewhat irregular; it represents accurately the average regimen of the river for the 20-year period.

From the "duration" curve, by integration, I deduce the "percent-deficiency" curve as shown in Fig. 5, for 1896 and 1909, the ordinates of which represent, in per cent, the amount that must be added to the flow to bring the minimum flow up to any assumed value; for example, in Fig. 5 for 1896 for a flow

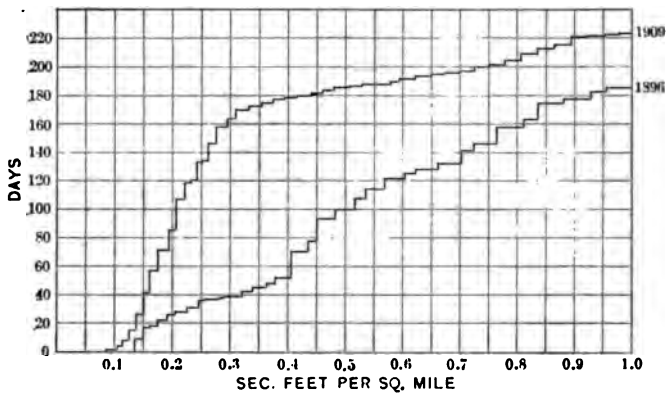

FIG. 4—DURATION CURVES OF THE SUSQUEHANNA RIVER AT MCCALL FERRY FOR 1909 AND 1896.

of 0.45 sec-ft. the deficiency is 8 per cent; this means that a quantity of water, 8 per cent of 0.45 = 0.036 sec-ft. for the entire year, would have to be added to the stream-flow to bring the discharge up to a minimum of 0.45 sec-ft. Otherwise stated, a total quantity of water equal to 0.036 sec-ft. for the year, or 0.036 × 8760 × 3600 cu. ft. added to the stream (from a reservoir, say,) at the needed times and in proper amounts, would maintain the minimum flow at 0.45 sec-ft. This amount would level up the valleys of the hydrograph, Fig. 2, to a uniform height of 0.45 sec-ft.

The "percent-deficiency" curves for 1909, the lowest year and for 1896, representing closely the average year of the 20-year period are given in Fig. 5; the actual 20-year average is

given in Fig. 6, which shows also the average "duration" curve for the period.

I have found the "percent-deficiency" curve to be the most convenient form for the use of stream-flow data; by assigning suitable values to the efficiency, the deficiency can be referred to the wheel shaft, to the power house busbar, to the substation busbar or to any other point of the power system. The energy to be supplied by the auxiliary plant is deduced directly from this curve by using the suitable efficiency; as, for example, assume the efficiency from the water to the substation busbar to be 65 per cent, then for a stream flow of 0.5 sec-ft. per sq. mi. and a head of 60 ft. the power at the substation busbar will be 1.65 kw. The deficiency, Fig. 6, being 10.4 per cent will equal 0.17 kw. average for the year, or 1500 kw-hr. If the deficiency at the power house busbar is to be determined, the correct effi-

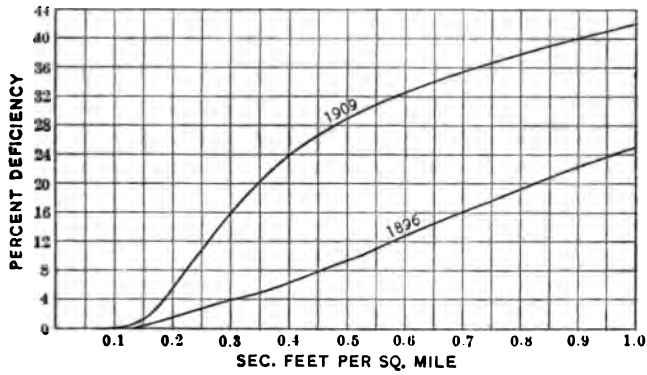

FIG. 5—PERCENT-DEFICIENCY CURVES OF THE SUSQUEHANNA RIVER AT MCCALL FERRY FOR 1909 AND 1896.

ciency would be, say, 80 per cent, and the energy deficiency would be increased in the ratio of the efficiencies and would become 1850 kw-hr.

As Fig. 6 shows, the average duration curve is nearly a straight line, and as an approximation, a straight line may be assumed. Fig. 6A shows the points determining the average duration curve, together with a straight line drawn to suit these points as closely as possible. The lower values of stream-flow and the higher values are given less weight, the line being drawn through the intermediate values, since the intermediate values are of more consequence for a power development.

For the purpose of determining the energy deficiency when there is no pondage, in the manner explained below, this approxi-

mation is sufficient. In all cases where the approximation will suffice, the deficiency in stream-flow, is calculated as follows:

Let

Q = any stream-flow.
Q_0 = minimum stream-flow.
D = days from duration curve.
d = a constant,—the number of days required to increase the flow by one sec-ft.

Then

$$Q = Q_0 + D/d \tag{1}$$

and percent-deficiency $= 100 \frac{Q-Q_0}{2} . D/365\, Q$

$$= \frac{1}{7.3} \left\{ 1 - \frac{Q_0}{Q} \right\} D \tag{2}$$

The percent-deficiency curve fixes the increased cost per kilowatt-hour of the total combined hydraulic and steam supply, for plants with pondage, when the total cost per kilowatt-hour of the steam supply is a constant amount, as for example, if it is obtained by contract at so many mills per kw-hr. Assume the total cost per kilowatt-hour of the steam supply to be 10 mills; then, if the hydraulic development is carried to the point at which the percent-deficiency is, say, 12 per cent, then 12 per cent of the total output is supplied by the steam plant, and therefore, the cost per kilowatt-hour of the combined supply is increased by 12 per cent of the unit cost of the steam supply.

This is sufficiently obvious, inasmuch as the added annual expense, on account of the steam plant, is equal to 12 per cent of the total output multiplied by the cost per kilowatt-hour of the steam supply. In other words, the steam supply increases the over-all cost per kilowatt-hour by the amount which is given directly by the percent-deficiency curve, when the cost per kilowatt-hour of the steam supply itself is a constant unit price. This is not true when the cost of the steam supply is an amount proportional to its capacity plus an increment proportional to its output; this, the general case, will be discussed below.

This curve, therefore, determines one of the principal factors that fixes the economical size of the auxiliary plant. As an illustration, assume that in the given market the " continuous "

supply can be sold for 2 mills per kilowatt-hour more than the variable supply will bring. Allowing a certain margin, an additional cost of the total supply of 1.5 mills per kilowatt-hour may be justified, thus leaving a margin of 0.5 mills for profit. The

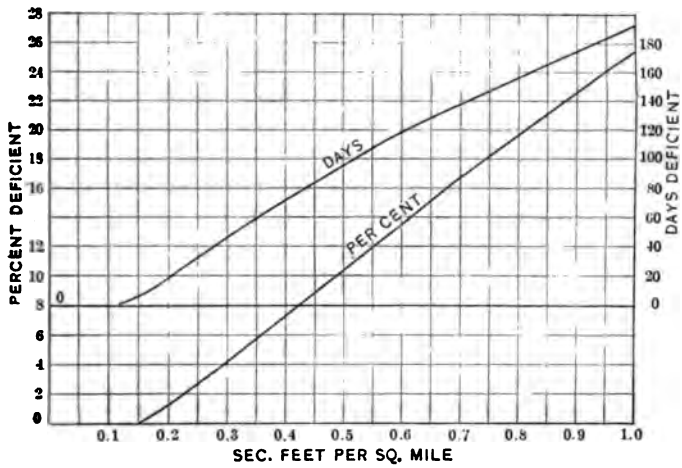

FIG. 6—AVERAGE PERCENT-DEFICIENCY AND AVERAGE DURATION CURVES FOR THE SUSQUEHANNA RIVER AT MCCALL FERRY FOR THE TWENTY YEAR PERIOD 1891-1910.

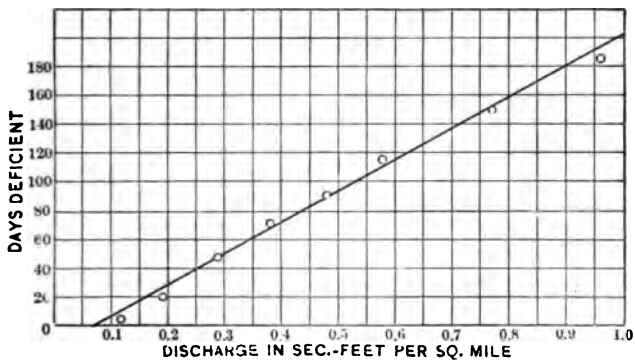

FIG. 6A—AVERAGE DURATION CURVE: STRAIGHT LINE ASSUMED FOR APPROXIMATE PURPOSES—EQUATION OF CURVE—

$$Q = 0.08 + \frac{D}{220}$$

development should then be fixed at such a point that the burden of the auxiliary supply when spread over the total output will amount to not more than 1.5 mills per kilowatt-hour. Assume also that it is known, from the conditions of operation, that the

total annual cost of the auxiliary supply will be 10 mills per kilowatt-hour; then the hydraulic plant should be developed to the point where the deficiency is 1.5/10 or 15 per cent of the total output. Fig. 6 shows at once that this deficiency, for this stream, is reached at a stream-flow of 0.645 sec-ft.; the plant then should be designed for 0.645 sec-ft.

This brings out clearly the great importance of the cost of the auxiliary supply. If, instead of 10 mills the cost is 7.5 mills per kw-hr., then, other conditions being the same, the plant should be developed for a stream-flow giving 1.5/75, or 20 per cent deficiency and Fig. 6 shows this to correspond to a stream-flow of 0.815 sec-ft., an increase of 26 per cent in economical capacity, due solely to the change in the unit cost of the steam supply from 10 to 7.5 mills per kw-hr.

TABLE II.

SHOWING INCREASED COST DUE TO AUXILIARY SUPPLY, FOR SEVERAL BASES OF DEVELOPMENT: PLANTS WITH PONDAGE.

	I	II	III	IV
1. Basis of development....sec-ft. per sq.mi.	0.25	0.5	0.75	1.0
2. Assumed head.....ft.		100		
3. Efficiency to substation.....per cent		67		
4. Power at substation.....kw.	1.43	2.85	4.27	5.7
5. Annual energy output...thousand kw-hr.	12.50	25.0	37.50	50.0
6. Percent deficiency for average year (Fig. 6).....per cent	2.7	10.4	18.2	25.4
7. Percent-deficiency for lowest year (Fig. 5).....per cent.	10.7	28.9	36.8	43.0
8. Assumed total cost of steam supply per kw-hr..... mills		10		
9. Increased cost of total supply per kw-hr. for average year.....mills	0.27	1.05	1.81	2.54
10. Increased cost of total supply per kw-hr. for lowest year.....mills	1.87	2.89	3.68	4.30

Table II gives data of this kind, for the stream in question, on four assumptions as bases of a development, viz., 0.25, 0.5 0.75 and 1.0 sec-ft. per square mile. In order to make the case concrete a head of 100 ft. is assumed. The other data of the table follow directly from these assumptions and from the curves already given. Item 6 gives the percent-deficiency in the average year, and from what has been said above, it follows at once that the increased cost per kilowatt-hour of the total supply is directly proportional to these figures, when the unit cost of

this supply is constant; for a 10 mill cost the increment costs are given by item 9, for the average year. In the long run, the costs for the average should be controlling, but it is well to know what would be the operating results in the lowest year. Item 7 from Fig. 5 gives the percent-deficiency for the lowest year and item 10, the increased cost per kilowatt-hour for the lowest year. It will be seen that on a basis of 0.5 sec-ft. per sq. mi. the increase for the average year is only 1.05 mills, but for the lowest year this increased cost runs up to 2.89 mills. In other words, in the lowest year the operation of the plant would be conducted at a loss; this would be offset by the good years, when the increased costs would be practically nothing.

For the sake of comparison, the percent-deficiency and dura-

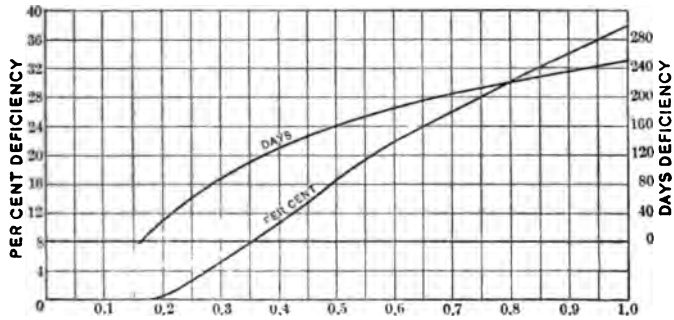

FIG. 7—AVERAGE PERCENT DEFICIENCY AND AVERAGE DURATION CURVES FOR THE POTOMAC RIVER AT AQUEDUCT DAM FOR THE 15-YEAR PERIOD 1897-1911. DRAINAGE AREA 11,400 SQUARE MILES.

tion curves of the Potomac at Aqueduct Dam for the 15-year period, 1897-1911, are given in Fig. 7. These curves bring out the material differences in the hydraulic characteristics of these two streams, occupying adjacent drainage areas. For a flow of 0.6 sec-ft., the Susquehanna shows a deficiency of 119 days and 13.5 per cent; whereas the Potomac shows a deficiency of 184 days and 21.7 per cent. If then, plants were developed at these streams for a flow of 0.6 sec-ft., the cost of the steam reserve for the Potomac would be materially greater than that for the Susquehanna, as 8.2 per cent more of the total energy would have to be supplied by steam. If the total cost of the steam supply were 10 mills, then for the Potomac the addition to the hydraulic cost would be 2.17 mills per kw-hr.; whereas for the Susquehanna the addition would be only 1.35 mills.

Another way to consider the relative value of the two streams is to determine the development for which the percent-deficiency will be the same. For the Potomac the deficiency of 13.5 per cent corresponds to a stream flow of approximately 0.46 sec-ft. That is, based on equal energy deficiency and consequently, the same size and output of steam plant, when operating on the same load curve, the economical development for the Susquehanna would be 30 per cent greater than for the Potomac. The difference is really greater, since a hydraulic development for greater capacity will generally mean a reduced unit cost. The plans under consideration for the Potomac at Great Falls are for a development at 0.6 sec-ft.

For plants without pondage it is necessary to consider the shape of the load curve in determining the deficiency. This is gone into further on.

Characteristics of the Load

It remains to consider the other factor in the determination of the economical limit of the development, that is, the characteristics of the load supplied. In any consideration of this kind, assumptions must be made in respect to the form of the load curve. Usually, so called representative load curves are made by averaging the loads for different months of the year and the average results represented somewhat as shown in Fig. 8, which represents a combined lighting and traction load of a large city. This curve is plotted with the maximum power as 100 instead of in kilowatts: that is, the ordinates are reduced to a percentage basis. This is done to give greater generality, just as the hydraulic curves were plotted in sec-ft. per sq. mi.

From the usual load-curve shown, there is derived a curve that I call the "percent-load" curve, for want of a better name. This is shown at $Y\,R\,P\,L\,X$, Fig. 8. The ordinates of this curve give the relative power, with maximum power at 100, and the abscissas give the "peak-energy" expressed in terms of the total energy as 100. Referring to Fig. 8, the abscissa $O\,K$ of the point P gives the percentage of the total energy that is included above the power line $N\,Q\,P\,U$. The co-ordinates are then "peak-energy" and "base-power." "Base-energy" and "base-power" might have been used, but the choice made simplifies the use of the curve. "Base-energy" is given by the abscissa measured to the left from X, that is, "base-power" is $K\,P$ and "base-energy" $K\,X$: "peak-power," $N\,Y$, and "peak-energy," $N\,P$.

This curve is made up of two parts, a straight line from X up to the point L of minimum power, $M\ S\ L$, and a curve tangent to this straight line $X\ L$ at the point L. This part $X\ L$ is straight, because energy and power are directly proportional up to the point of minimum power.

This "percent-load" curve possesses several interesting properties:

1. A tangent at the point L, that is, the line $X\ L$ continued,

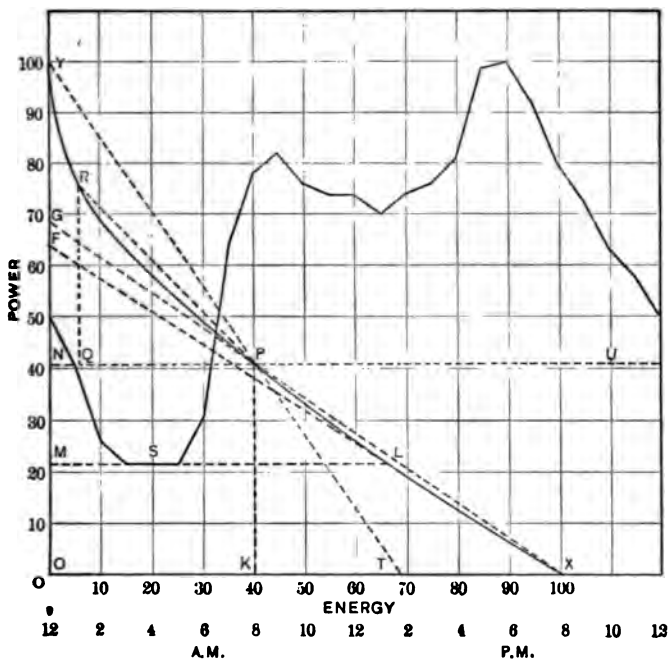

FIG. 8—ORDINARY LOAD CURVE AND PERCENT-LOAD CURVE CORRESPONDING TO IT.

intercepts the Y-axis at the point F, and $O\ F$ is the load-factor of the total load.

2. A line drawn from Y through any point P will intersect the X-axis at point T, and the load-factor of the peak-load above P is equal to the load-factor of the total load $O\ F$ multiplied by $O\ T$ or $O\ F.\ O\ T$.

3. A line drawn from X through the point P intersects the Y-axis at the point G, and the load-factor of the base-load is $O\ F/O\ G$.

These theorems can be proved in a simple manner. Consider any two points P and R on the " percent-load " curve; the energy between them is proportional to the difference between the abscissas of the two points, that is to $P\,Q$: the power is proportional to the differences between the ordinates, that is to $R\,Q$: the load-factor of the load between these two points is then proportional to $P\,Q/R\,Q$, that is to the tangent of the angle $Q\,R\,P$. The load-factor is then equal to the tangent of this angle multiplied by a factor of proportionality.

Consider now the points Y and X, that is, the total load: the load-factor is here proportional to the tangent of the angle $O\,Y\,X$ multiplied by the same factor; but the tangent $O\,Y\,X$ is unity, hence the load-factor, " f " of the total load is the factor of proportionality; the load-factor of the load between P and R is then equal to $f \tan Q\,R\,P$. This is the general theorem and the others are special cases; they are deduced as follows:

Consider the peak-load above P; the load-factor is equal to $f \tan N\,Y\,P = f \tan O\,Y\,T$; that is $= f\,O\,T$.

Again, consider the load below P; the load-factor is equal to $f \tan K\,P\,X = f \tan O\,G\,X = f/OG$.

Consider, further, the point " L;" the load-factor of the base-load is f/OF; but L being the point of minimum load, this load factor is unity. Hence $O\,F = f$. That is, the load-factor of the total load is represented by the intercept on the Y-axis made by the tangent to the curve at L.

Otherwise stated, (see Fig. 9),

1. Load-factor of total load $= O\,F$
2. " " " peak-load $= O\,F.\,O\,T$
3. " " " base-load $= O\,F/O\,G$
4. " " " load between P and R $= O\,F \tan Q\,R\,P$

This curve enables one to determine at once the capacity of the steam plant required to meet any assumed conditions of the hydraulic development, for plants with pondage. In fact, the curve itself gives the capacity of the steam plant for any ratio of minimum to rated stream-flow. This can be seen by reference to Fig. 9, on which is reproduced the percent load curve of Fig. 8, for the sake of clearness. The abscissa of any point of the curve is the ratio of peak-energy to total energy. It therefore represents, for plants with pondage, the ratio of minimum stream-flow to rated stream-flow, since the ratio

of stream-flow is the ratio of hydraulic energy available for use to total energy required by the load, and the hydraulic energy is used for the peak-load. The ordinate of the point represents base-power, which is the portion of the load not supplied by the hydraulic plant and which must be supplied by the steam plant. In other words, this curve represents, for plants with pondage, the relation between the ratio of minimum flow to rated flow and the capacity of steam plant required, in per cent of maxi-

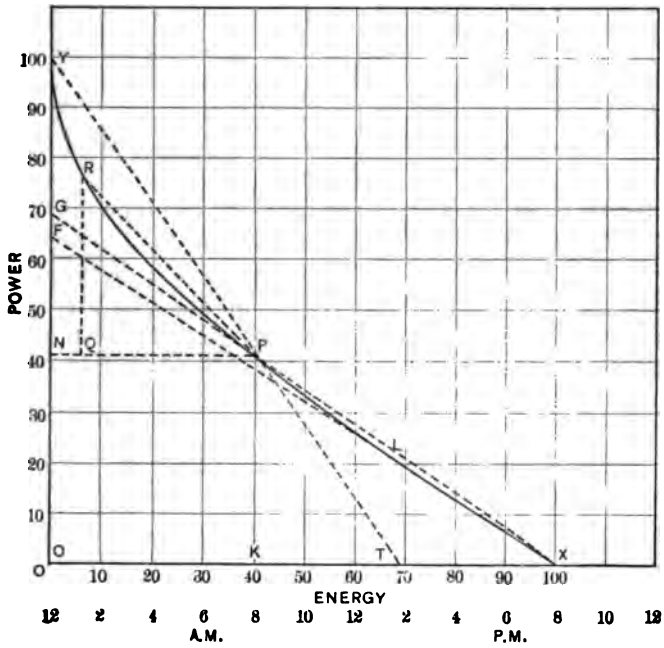

FIG. 9—PERCENT-LOAD CURVE OF A LARGE CITY SHOWING THE COMBINED POWER, LIGHTING AND TRACTION LOADS.
ORDINATES: BASE-POWER
ABSCISSAS: PEAK-ENERGY

mum power. For instance for a minimum flow of 20 per cent of the rated flow, the capacity of the steam plant required is 58 per cent of the maximum power; for a ratio of minimum flow to rated flow of 50 per cent, the capacity of the steam plant required is 33 per cent. This load-curve then gives at once the capacity of the steam plant required for the entire range of operating conditions.

For plants without pondage, the greatest proportion of the possible energy of the stream-flow, under low water conditions,

can be made available by supplying the base-load from the stream up to its power capacity. If the flow is 20 per cent of the rated flow, then the steam plant will have a capacity of 80 per cent of the maximum. It should be noted also that the rated-stream flow, for plants without pondage, is equal to the rated flow for plants with pondage multiplied by $1/f$, assuming the same load curve, *i. e.*, the maximum in one case, the average in the other.

The determination of the energy deficiency for plants without pondage is less simple than in the case of pondage. This is due to the fact that without pondage a portion of the hydraulic energy is wasted. Referring to Fig. 8, when the stream-flow corresponds to $O\ N$, then all the energy represented by the hollow of the load curve below the line $N\ Q\ P$ is wasted. It is clear that it is more economical to supply the peak-load from the steam plant and the base-load from the stream. If when the stream-flow is, say $O\ N$ or 41 per cent, the peak-load is supplied by the stream, only about 19 per cent of the total energy comes from the stream. If on the other hand, the stream supplies the base-load up to the 41 per cent point then, as Fig. 9 shows 60 per cent energy is utilized. As the size of the steam plant will be the same in both cases, that is, 59 per cent of the peak, it is clear that the hydraulic energy should be used for base-load.

To calculate the energy-deficiency in this case, assume, for example, that the maximum power corresponds to $Q_m = 0.5$ sec-ft.; then when the stream-flow is equal to Q_m, the steam plant will be called on for no energy; when the stream-flow is $0.8Q_m$ the steam plant will supply the peak above 80 per cent or 4.0 per cent of the energy (Fig. 9). The average duration curve, (Fig. 6) shows that for 96 days of the year the flow is less than 0.5 sec-ft. and for 73 days less than 0.4 sec-ft.; that is, for 23 days the flow will be between that required for maximum power and 80 per cent power. The steam plant will be supplying, during these 23 days, energy varying from nothing to 4 per cent, an average of 2 per cent; the total output of the steam plant for this period will then be proportional to 23×2 per cent. This procedure, carried out step by step and the results summed up and averaged, will give the energy to be furnished by the steam plant during the low-water period, for the load curve used.

But this method is somewhat tedious and the data is not sufficiently accurate to justify any refinement; hence an approximation is developed, based on the assumption that the average

duration curve may be represented sufficiently well for this purpose by a straight line.

That this average duration curve is nearly a straight line is shown in Fig. 6A where the actual points, and the assumed straight line are shown; the equation of the line is

$$Q = Q_0 + D/d \qquad (3)$$

$$Q = 0.08 + D/220 \qquad (3a)$$

This equation means that any fixed increase or decrease in the flow will take place in the same number of days, that is, the number of days that the flow is between 0.2 and 0.3 sec-ft. is the same as the number when it is between 0.9 and 1.0 sec-ft. As the stream-flow is directly proportional to power, this means that the number of days used as the multiplier in the illustration, is the same for all parts of the percent-load curve, when the interval in stream-flow, and consequently in power, is constant. The energy supplied by the steam plant between 100 per cent and 90 per cent power is then the average of the abscissas of these points multiplied by a definite number of days. Similarly between 30 per cent and 20 per cent the energy supplied is the average of the abscissas multiplied by the same number of days. The sum of these abscissas, taken sufficiently closely and multiplied by the power difference, or time difference, is directly proportional to the area of the percent-load curve from the peak down to the point of low-flow considered.

The duration in days corresponding to a fixed per cent difference in power, as 10 per cent, is clearly directly proportional to the flow corresponding to maximum power, Q_m; if $Q_m = 1.0$ sec-ft. then 10 per cent power corresponds to 0.1 sec-ft., and to 22 days from eq. (3a). But if Q_m is 0.5 sec-ft., then 10 per cent power corresponds to 0.05 sec-ft., and to 11 days. The per cent energy deficiency is then proportional to the flow for maximum power Q_m.

It can easily be shown that the energy deficiency in per cent.

$$p_e = 100\, Q_m \times d/365 \times \left(\frac{\text{Area above } P_0}{10^4}\right) \qquad (4)$$

As 10^4 represents the area of the square enclosing the curve $Y\,R\,P\,L\,X$, the ratio of the areas is shown graphically; (d) is the number of days to increase the flow by one sec-ft., Q_m the flow corresponding to maximum power.

The practical way to calculate this deficiency is to take the abscissas of the average power interval, add them up, multiply by the corresponding number of days and divide by 365, thus getting the average per cent deficiency.

For example:

Q_m = 1.0; 10 per cent power intervals; days corresponding to 10 per cent = 22

Q_0 = 0.2 sec-ft.

Calculate the average peak-energy for each step of 10 per cent of the power down to the minimum power, 20 per cent, as follows:

Average peak-energy between power values of	Per cent
100–90	0.5
90–80	2.5
80–70	6.8
70–60	14.0
60–50	23.7
50–40	35.0
40–30	47.5
30–20	61.5
Sum	191.3

Hence average percent-deficiency = 191.3 × 22/365
= 11.5 per cent.

If Q_m had been 0.5, then the number of days corresponding to the 10 per cent power interval would have been 11, and the per cent-deficiency would have been 11.5/2 = 5.75 per cent.

It is simpler and sufficiently accurate to take the abscissa of the average power ordinate for each step, instead of the average of the abscissas of the two limiting power values.

Typical Percent-Load Curves

This completes the consideration of necessary capacity of the steam plant and its output, for hydraulic plants both with and without pondage, and for any stream flow corresponding to the rated capacity.

The method then depends upon the use of three curves; the "percent-deficiency" and the "duration" curve, characterizing the hydraulic features of the development and the "percent load" curve, characterizing the power load. It remains now to show how the results so far arrived at, can be applied to determine the increased cost of the auxiliary supply and consequently the economical point of the development, considered in the light of the actual conditions of the power market.

Before doing this, however, some examples of percent-load curves will be given, in order to bring out the variation of these curves with different conditions.

Fig. 10 gives the percent-load curve of a medium size traction system with some light and power service, in an eastern city; the maximum power of this load was approximately 15,000 kw. The curve is that of a single day, not an averaged curve. Fig. 11 gives the curve for a traction system of a western city, the maximum power being approximately 7000 kw. An examina-

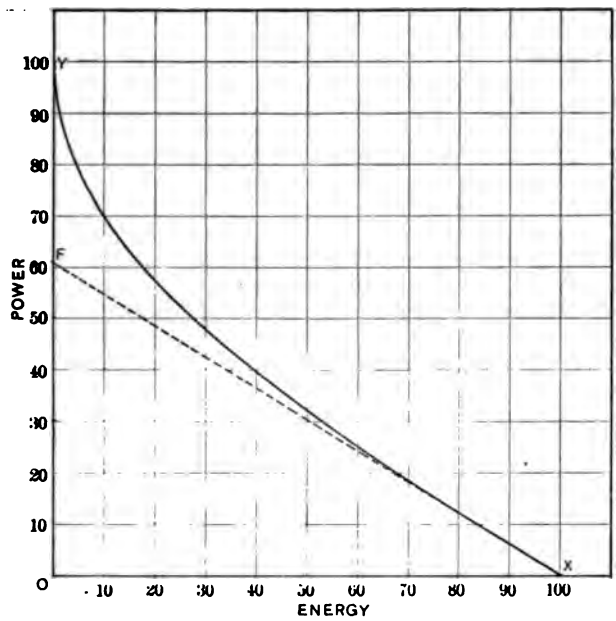

FIG. 10—PERCENT-LOAD CURVE OF MEDIUM SIZE TRACTION SYSTEM IN AN EASTERN CITY.

tion of these two curves shows that of Fig. 11 to be a more peaked curve. For instance Fig. 11 contains less than six per cent of the energy in the 30 per cent peak, whereas Fig. 10 shows 10 per cent. Fig. 11 shows 21 per cent of the energy for the 50 per cent peak, whereas Fig. 10 shows 28 per cent. The total load-factors do not differ greatly, being 54 per cent in the one case and 61 per cent in the other.

Figs. 12 and 13 show the percent-load curves for the same system, Fig. 12 being the averaged curve of twelve Saturday curves, one for each month of the year, and Fig. 13 the averaged

curve of the twelve succeeding Mondays. These show well the difference in the characteristics of the load of the same system for different days. This difference would be reflected in the capacity of the steam plant required for reserve. With a stream-flow of 20 per cent of the rated flow, (with pondage), the load of Fig. 12 would require a steam plant of 50 per cent capacity, whereas, the load of Fig. 13 would require only 44 per cent. For a 10 per cent ratio, Fig. 12 requires 70 per cent and Fig. 13, 59 per cent.

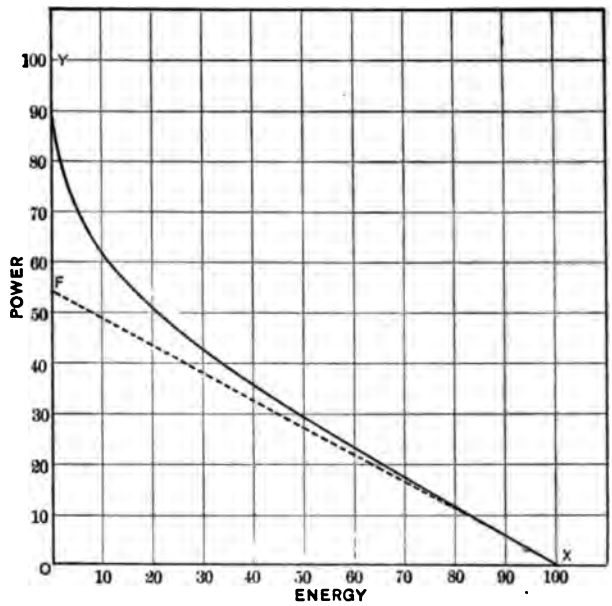

FIG. 11—PERCENT-LOAD CURVE OF A MEDIUM SIZE TRACTION SYSTEM IN A WESTERN CITY.

Fig. 14, is to show the difference in capacity of steam plant required for loads having the same total load-factor, but differing in shape. The four load curves shown, all have a total load-factor of 40 per cent; but with a ratio of low flow to the rated flow of 25 per cent, as indicated by *O T*, the steam plant capacity required will be 33, 42.5, 54 and 59 per cent of the maximum respectively. The percent-load curve therefore, brings out clearly the fact that the total load-factor is not the determining factor in fixing the capacity of the auxiliary steam plant.

Fig. 15 gives the " annual percent-load " curve of the light-

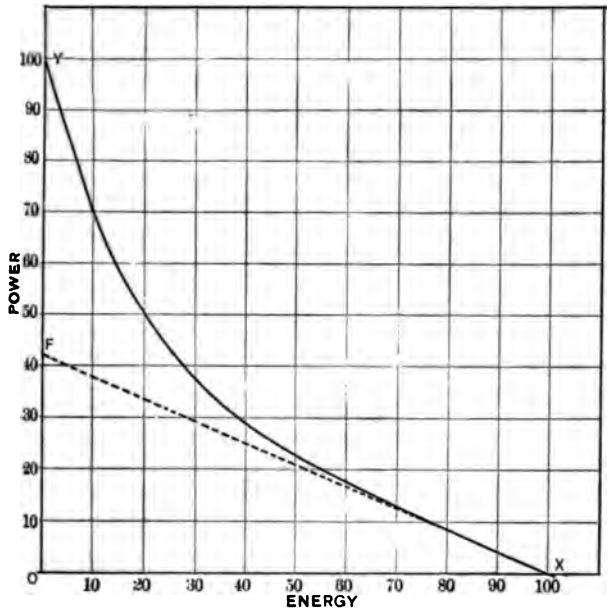

FIG. 12—PERCENT-LOAD CURVE OF THE AVERAGE SATURDAY LOAD OF A MEDIUM SIZE LIGHT AND POWER SYSTEM.

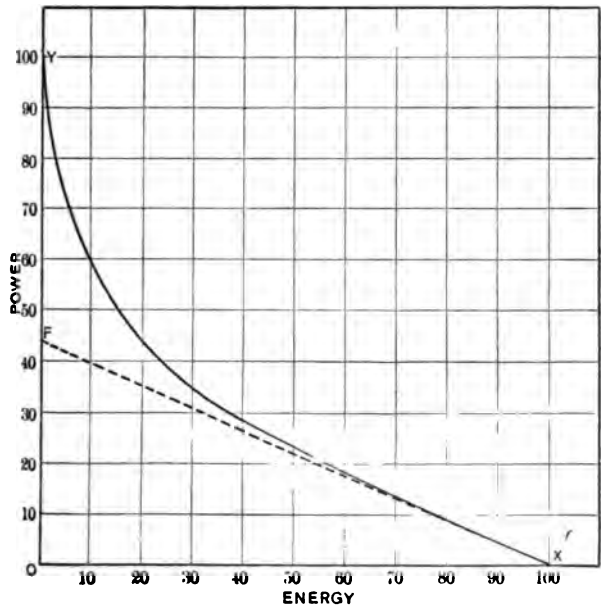

FIG. 13—PERCENT-LOAD CURVE OF THE AVERAGE MONDAY LOAD OF THE SAME SYSTEM AS FIG. 12.

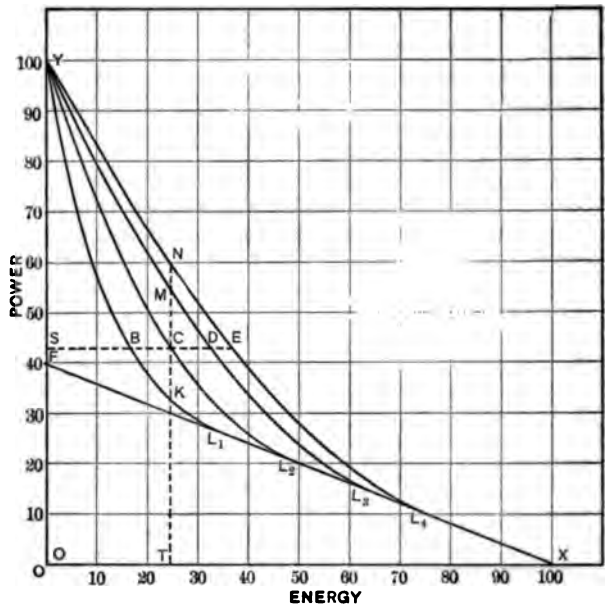

FIG. 14—PERCENT-LOAD CURVES WITH SAME LOAD FACTOR, SHOWING DIFFERENT AUXILIARY POWER REQUIREMENTS.

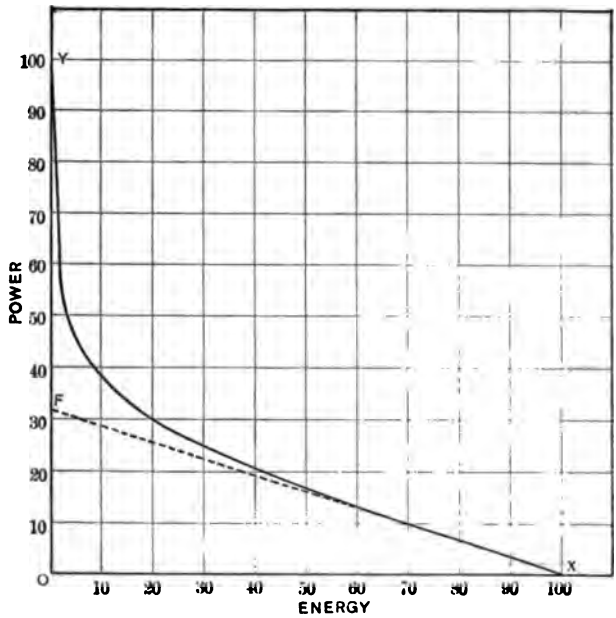

FIG. 15—ANNUAL PERCENT-LOAD CURVE OF A LIGHT AND POWER SYSTEM OF A WESTERN CITY.

ing system in a western city. This curve is made up from a large number of representative curves for different periods of the year; as for instance, one load curve being taken to represent each week; the maximum annual power is taken at one hundred and the maxima of the load curves representing the different periods of the year at their appropriate values. From these curves the energy above any particular value of the power is calculated for each curve and the different amounts summed up to give the total energy above that value of the power for the entire year. In other words, this curve represents, with the year as the unit of time instead of the day, the relation of peak-energy and power. Curves of this character should be used to determine the steam reserve when plants with large reservoir capacity, as distinguished from pondage, are under consideration; the same general methods will apply to such a problem as to those I have considered, but it is not my purpose at present to consider this problem further than to give an illustration.

Suppose that the load represented by the curve of Fig. 15 is to be supplied and that a reservoir capacity of different amounts can be obtained at increasing expenditures. If a reservoir capacity equal to 10 per cent of the energy is available a steam plant of 38.5 per cent will be required. If a reservoir capacity equal to 20 per cent is provided, the steam plant capacity is reduced to 30 per cent. That is, by doubling the reservoir capacity, the steam plant capacity is reduced from 38.5 per cent to 30 per cent of the maximum load and the question to be determined is whether the additional annual cost of the double reservoir capacity or the additional annual cost of the steam plant and its operation will be greater.

The duration and the percent-load curves so far considered have been for the entire year; such curves can, however, be compiled for each month of the year and with percent-load curves representing the load for each month, the determination of the steam plant capacity can be made for each month. Where conditions are known with sufficient accuracy, the consideration of the monthly regimen of the stream may be justified. The method to be used does not differ in any respect from that discussed. It becomes merely a question of considering, say, twelve sets of curves instead of one set. The actual use of these curves is so simple that the additional labor required is negligible.

The minimum flow of the stream to be used may be the ab-

solute minimum, the minimum of the average year, the average minimum, or some other value of low discharge of the stream. The selection of the particular value to be used depends upon the degree of insurance of the continuity of the supply that is justified by the conditions. The added cost of the insurance of the supply should be equated to the losses, direct and indirect, sustained by failure of the supply. If it is planned to secure absolute continuity, in as far as stream-flow is concerned, it will be necessary to use the absolute minimum of the stream and to use it in connection with the maximum load that can occur upon any day when the stream-flow may be lowest. This degree of insurance is seldom necessary; usually it will be sufficient to use the stream-flow which can be depended on for, say four years out of five; in other words, to eliminate the extraordinarily low discharge which will occur once in every five to ten years. But on this point, as in all others in connection with the matter, the decision depends upon the experience and judgment of the engineer, and no hard and fast rule can be laid down. One kind of load demands the highest degree of insurance, whereas loads of a different character may be satisfactorily served with a less degree of insurance.

Cost of Hydroelectric Plants

This completes the description of the method of determining the capacity and output of the auxiliary steam plant required for any conditions of load and stream-flow. It is seen to depend on the use of two curves, the percent-deficiency curve and the percent-load curve. For plants with pondage, the ratio of low-flow to rated-flow fixes the capacity of the steam plant, through the use of the percent-load curve, and its energy output is determined by the percent-deficiency curve. For plants without pondage, the capacity of the steam plant is fixed by the ratio of the low-flow to rated-flow and its output is determined by the percent-load curve.

The application of this method depends upon the determination of the cost of an hydroelectric development at any given site over a range of capacities. The cost per kilowatt for the development for low stream flow will obviously be very high, but will decrease as the rated flow of the development increases. In order to use the method, it is necessary to know the annual cost of the hydraulic development per kilowatt of its capacity throughout the range of capacities under consideration, inasmuch as this cost added to the annual cost of the steam plant gives the total annual cost of the combined plant per kilowatt. In

any specific case detailed estimates of the total cost of the hydraulic development for the range of capacities should be used, but in order to discuss the matter generally some assumption must be made covering the cost per kilowatt of a hydraulic development at a given site, for several capacities of equipment.

The cost of any hydroelectric development is made up of certain items that are independent of the capacity of the equipment installed and others proportional to the capacity; in most hydroelectric plants, the fixed costs are materially greater than the variable costs. The relative amounts of these two items vary with the different character of plants, but within a reasonable range of capacity, the assumption that total cost is a constant plus an amount proportional to capacity is sufficiently true to serve in a discussion of this kind. In any concrete case, the accurate method to determine cost for various capacities is to make detailed estimates for the several projects.

TABLE III.

RELATIVE COST OF SOME HYDROELECTRIC PLANTS.

Plant No.	Proportion of Total Cost that is Fixed	Variable
1	70 per cent	30 per cent
2	72 "	28 "
3	40 "	60 "
4	72 "	28 "
5	72 "	38 "
6	58 "	42 "
7	67 "	33 "
8	68 "	32 "
9	77 "	23 "
10	76 "	24 "
11	77 "	23 "
12	68 "	32 "
Average	68 per cent	32 per cent

Table III gives the division between the fixed portion of the cost and the variable portion for twelve different plants, covering high head, medium head and low head plants, some with flumes, canals, or pipe lines, and others with heavy concrete dams and no water-ways. The data of this table are taken from a number of sources; several are my estimates, some are from the reports of other engineers and others are from published

statistics. In some cases, detailed estimates have been prepared by the engineer for several different capacities; in others, the items of cost as given for the normal development are divided into an assumed fixed part and a variable part; the variable part is then taken to be proportional to the capacity.

The data of this table may be somewhat surprising. One would probably think that the cost of an hydraulic plant for high head with flume lines, canals, penstocks, and without storage, would be in greater part proportional to capacity, than would a plant with a large concrete dam and no waterways. But the preliminary costs, riparian rights, removal of railroads and roads, real estate, right-of-way for transmission line, charters, legal expenses, banker's expenses, and various items that are not directly dependent upon the capacity, together with that part of the cost of the equipment which is in itself not directly proportional to capacity, make up a large part of the total cost, even in such cases.

For want of a better generalization covering the cost of an hydraulic development, it will be assumed that the total cost is composed of a fixed portion plus a portion proportional to the capacity; it being always kept in mind that this is done simply to illustrate the method described and not as an attempt to formulate a general rule. The results from this assumption check well, in certain cases, with detailed estimates based on actual figures of cost of developments at the same site, for various capacities.

TABLE IV.

VALUES OF $k_r = (a/r + b)$

r	$a = 0.75$, $b = 0.25$	$a = 0.67$, $b = 0.33$	$a = 0.60$, $b = 0.40$	$a = 0.50$, $b = 0.50$
0.5	1.75	1.67	1.60	1.50
1.0	1.00	1.00	1.00	1.00
1.5	0.75	0.78	0.80	0.83
2.0	0.63	0.67	0.70	0.75

Let, then,

a = the part of the cost of the plant, in per cent, that does not vary with the capacity,

b = the part that is proportional to capacity,

r = the ratio of the capacities, taking some intermediate capacity of plant as unity, in order that the range in capacity may be kept as narrow as may be.

Then the ratio of total cost of plants for various capacities is represented by $(a + r\,b)$
and the ratio of the cost per kilowatt of capacity is

$$k_r = (a/r + b) \tag{4}$$

For plants both with and without pondage, the ratio of capacity is the ratio of rated stream-flow, since the same load curve is assumed for the several capacities, that is the same power market.

If then, Q_1 is the stream-flow for the basic capacity, *i.e.* for $r = 1$ and Q_r is for any other capacity,

then $$r = Q_r/Q_1. \tag{5}$$

The annual charges on a hydroelectric plant are practically independent of the energy output; this is strictly true for the fixed charges, such as interest, depreciation, insurance, taxes, etc., and is approximately true for the cost of management. Inasmuch as the investment cost per kilowatt of the combined plants will vary over a wide range, profit must be included with fixed charges in order to determine the economical development. It is assumed that there is market at a known price and the question is to determine at what price energy can be sold from the various developments; therefore selling price and not cost must be determined. In what follows, I take for the fixed charges for the hydroelectric and steam plants the following:

TABLE V.

	Hydroelectric	Steam
Interest and profit	10 per cent	10 per cent
Depreciation and obsolescence	2 "	7 "
Insurance and taxes	1 "	2 "
Management	1 "	1 "
Total	14 per cent	20 per cent

Depreciation in a hydroelectric plant affects only a small portion of the total development, the equipment; whereas in a steam plant practically the entire plant is subject to depreciation. Similarly, obsolescence due to changes in the art is practically non-existent in an hydroelectric plant, since the plant can-

not be changed in any reasonable way in order to obtain a higher efficiency, whereas with a steam plant it is well known there is a constant change due to the improvements in the economy of machines. The fundamental reasons for the greater permanence for the hydraulic plant is the fact that the efficiency of the conversion of energy in this case is high, say 80 per cent, whereas with a steam plant it will not exceed 12 per cent. The margin for possible improvement is then very small in the one case and very great in the other. Further, the hydraulic plant, once built, cannot well be radically changed, even though the efficiency of the waterwheels should be made greater, and if such changes could be made they would not be economical, owing to the great cost of changes in the entire construction of the plant.

Insurance and taxes are less for the hydraulic plant on account of the different character of the property, and also due to the fact that the plant itself is usually in a country district where the tax rate is lower than in a city.

The cost of operation and maintenance of a hydroelectric plant is practically independent of its output, and only in part proportional to its capacity. It is, however, relatively to fixed charges and profit, so small that no error of moment will be made by assuming it to be proportional to capacity.

The total annual cost will then be as follows:

Let

i_h = the sum of all charges and profit, in per cent

C_h = the capital cost of the plant per kw. of maximum capacity at basic rating, *i.e.* for $r = 1$.

O_h = the total operating and maintenance cost per kw. for basic capacity,

$k_r = a/r + b$ = the ratio of cost per kw. to basic cost.

Then will

$$\text{Total annual cost per kw.} = A_h = i_h k_r C_h + O_h k_r$$
$$= k_r (i_h C_h + O_h) \qquad (6)$$

Annual Cost of Steam Plant

To this annual cost must be added the total cost of the steam plant, determined for the conditions of operation fixed by the "percent-deficiency" and the "percent-load" curve. This is done as follows:

Let

c = the annual fixed charges in dollars on the steam plant per kw. of its own capacity, including interest, profit, depreciation, taxes, insurance and pay roll for the term during which the plant will be in commission, usually for 7 to 10 months, and also including a certain portion of the fuel, that part required to bank fires, or to keep the plant ready for quick operation.

m = the increment cost of energy production in mills per kw-hr. This will include only fuel and minor supplies.

p_e = the percent energy deficiency for the average year under the assumed conditions.

p_c = the relative capacity of the steam plant required to meet the assumed conditions.

h = the number of hours equivalent to the load-factor, from the percent-load curve, divided by 1000, *i.e.* $= f \times 8760/1000$, where f is the load-factor.

Then the annual cost of the steam plant per kw. of total load is

$$A_s = c\,p_c + h\,m\,p_e \tag{7}$$

A_s is the increased annual cost per kw. of total load, which is imposed by the steam plant.

From this, the increased cost in mills per kw-hr. of the total output due to the addition of the auxiliary steam plant is

$$A_s/h = c\,p_c/h + m\,p_e \tag{8}$$

The selling price is then given by

$$S = A_h + A_s \tag{9}$$

Examples of Use of Method

The application of this method to certain assumed conditions is given in the tables following. Example I gives the total annual cost for the Susquehanna for developments rated at 0.25, 0.5, 0.75 and 1.0 sec-ft. per square mile for a plant with pondage and for a load having a high load-factor of 64 per cent. The results are first calculated for an investment cost of $100 per kilowatt for the hydraulic plant, when developed for a rated flow of 0.5 sec-ft., and for an annual cost of $10 per kilowatt, covering the fixed charges of the steam plant, corresponding to an investment cost of $50 per kilowatt, if 20 per cent be taken for fixed charges. An addition is then made to the figures thus obtained to cover an investment cost of the hydraulic plant of

$150 per kilowatt and also to cover fixed charges at $15 per kilowatt for the steam plant. The annual cost for four different conditions is then given in the table; that is for hydraulic cost of $100 and annual steam cost of $10; hydraulic cost of $100 and annual steam cost of $15; hydraulic cost of $150 and annual steam cost of $10; hydraulic cost of $150 and annual steam cost of $15. Throughout, the increment operating cost of the steam plant is taken at 3 mills per kw-hr.

EXAMPLE I: Plant with pondage:

Load of Fig. 9, load-factor 64 per cent, $h = 5500/1000$,

Assume

$k_r = 0.67/r + 0.33$: $Q_r = 0.5$, for $r = 1$; minimum flow $Q_0 = 0.1$

$C_h = \$100$, $O_h = \$1$, $i_h = 14$ per cent.

Hence

$(i_h C_h + O_h) = \$15 = A_h/k_r$; $A_h = \$15\, k_r$;

Also $c = \$10$, $m = 3$ mills; $m\, h\, p_e = \$16.50\, p_e$.

TABLE VI.

1.	Rated stream-flow, Q_r, sec-ft.	0.25	0.50	0.75	1.00
2.	Ratio of capacity, $Q_r/0.5$	0.50	1.0	1.50	2.0
3.	Percent-deficiency, p_e, (Fig. 6)	2.7	10.4	18.1	25.4
4.	Minimum/rated-flow, $0.1/Q_r$	0.4	0.2	0.13	0.10
5.	Steam plant capacity, p_c, (Fig. 9)	0.41	0.58	0.65	0.69
6.	Hydraulic cost ratio, k_r (Table V)	1.67	1.00	0.78	0.67
7.	$\$10 \times p_c$ (line 5)	$4.10	$5.80	$6.50	$6.90
8.	$\$16.50 \times p_e$ (line 3)	0.45	1.72	2.95	4.20
9.	$A_s = (7) + (8)$ = Steam cost	4.55	7.52	9.45	11.10
10.	$A_h = \$15\, k_r$ = Hydraulic cost	25.00	15.00	11.70	10.00
11.	$S = A_s + A_h$ = Total cost	$29.55	$22.52	$21.15	$21.10
The increment to be added to line (11) for					
12.	$C_h = \$150$ is	$11.70	$7.00	$5.48	$4.70
13.	$c = \$15$ is	2.05	2.90	3.25	3.45
	And therefore for				
14.	$C_h = \$100$ $c = \$15$, S is	31.60	25.42	24.40	24.55
15.	$C_h = \$150$ $c = \$10$, S is	41.25	29.52	26.63	25.80
16.	$C_h = \$150$ $c = \$15$, S is	43.30	32.42	29.88	26.25

Example II embodies the same data as Example I, except that a load having a medium load-factor of 42.5 per cent is taken. Example III is the same as Example I except that a load having a low load-factor of 32 per cent is taken.

EXAMPLE II: Same as Example I, except that load-curve of Fig. 12 is used. Load-factor 42.5 per cent: $h = 3700/1000$

$m\, h\, p_e = \$11.40\, p_e$.

TABLE VII.

1. Rated stream flow, Q_r, sec-ft.	0.25	0.50	0.75	1.00
2. Ratio of capacity, $Q_r/0.5$	0.5	1.0	1.50	2.0
3. Per cent-deficiency, p_e, (Fig. 6)	2.7	10.4	18.1	25.4
4. Minimum/rated-flow, $0.1/Q_r$	0.4	0.2	0.13	0.10
5. Steam plant capacity, p_c (Fig. 12)	0.29	0.51	0.63	0.71
6. Hydraulic cost ratio, k_r (Table V)	1.67	1.00	0.78	0.67
7. \$10 $\times$ p_c (line 5)	\$2.90	\$5.10	\$6.30	7.10
8. \$11.40 $\times$ p_e (line 3)	0.30	1.15	2.06	2.82
9. A_e = (7) + (8) = Steam cost	3.20	6.25	8.36	9.92
10. A_h = \$15 k_r = Hydraulic cost	25.00	15.00	11.70	10.00
11. $S = A_e + A_h$ = Total cost	\$28.20	\$21.25	\$20.06	\$19.92
The increment to be added to line (11) for				
12. C_h = \$150 is	\$11.70	\$7.00	\$5.48	\$4.70
13. c = \$15 is	1.45	2.55	3.15	3.55
And therefore for				
14. C_h = \$100; c = \$15, S is	29.65	23.80	23.21	23.47
15. C_h = 150; c = 10, S is	39.90	28.25	25.54	24.62
16. C_h = 150; c = 15, S is	41.35	30.80	28.69	28.17

EXAMPLE III: Same as Example I, except that load-curve of Fig. 15 is used. Load-factor, 32 per cent, h = 2800/1000.
$m\,h\,p_c$ = \$8.40 p_e.

TABLE VIII.

1. Rated stream flow, Q_r, sec-ft.	0.25	0.50	0.75	1.00
2. Ratio of capacity, Q_r/O.5	0.5	1.00	1.50	2.0
3. Per cent-deficiency, p_e (Fig. 6)	2.7	10.4	18.1	25.4
4. Minimum/rated-flow, $0.1/Q_r$	0.4	0.2	0.13	1.10
5. Steam plant capacity, p_c (Fig. 15)	0.21	0.30	0.35	0.39
6. Hydraulic cost ratio, k_r (Table V)	1.67	1.00	0.78	0.67
7. \$10 p_c (line 5)	\$2.10	\$3.00	\$3.50	\$3.90
8. \$8.40 p_e (line 3)	0.22	0.87	1.52	2.23
9. A_e = (7) + (8) = Steam cost	2.32	3.87	5.02	6.13
10. A_h = \$15 k_r = Hydraulic cost	25.00	15.00	11.70	10.00
11. $S = A_e + A_h$ = Total cost	\$27.32	\$17.87	\$16.72	\$16.13
The increment to be added to line (11) for				
12. C_h = \$150	\$11.70	\$7.00	\$5.48	\$4.70
13. c = \$15	1.05	1.50	1.75	1.95
And therefore for				
14. C_h = \$100; c = \$15, S is	\$28.37	20.37	18.47	18.08
15. C_h = 150; c = 10, S is	39.02	25.87	22.20	20.78
16. C_h = 150; c = 15, S is	40.07	27.37	23.95	22.83

The results from these three cases are summarized in Table IX, which gives the total annual cost per year per kilowatt of combined hydraulic and steam plants, for the four conditions of investment and operating costs stated above. To this is

added a column giving the annual cost of an "all-steam" supply under the same conditions of load. The cost of the steam supply imposes an upper limit to the permissible cost of the combined hydraulic and steam plants, as it is obvious that it would be bad business to develop the combined plant unless a material saving in the total annual cost is thereby obtained.

TABLE IX.

TOTAL PRICE PER KILOWATT-YEAR—FROM TABLES VI, VII AND VIII—AND PRICE FOR AN "ALL-STEAM" SUPPLY.

Q_r = ...	0.25	0.5	0.75	1.00	All Steam
I For C_h = \$100: c = \$10					
1 Load-factor 64 per cent..	\$29.55	\$22.52	\$21.15	\$21.10	\$26.50
2 Load-factor 42.5 per cent	28.20	21.15	20.06	19.92	21.10
3 Load-factor 32 per cent	27.32	18.87	16.72	16.13	18.40
II For C_h = \$100: c = \$15					
1 Load-factor 64 per cent	31.60	25.42	24.40	24.55	31.50
2 Load-factor 42.5 per cent	29.65	23.80	23.21	23.47	26.10
3 Load-factor 32.0 per cent	28.37	20.37	18.47	18.08	23.40
III For C_h = \$150: c = \$10					
1 Load-factor 64.0 per cent	41.25	29.52	26.63	25.80	26.50
2 Load-factor 42.5 per cent	39.90	28.25	25.54	24.62	21.10
3 Load-factor 32.0 per cent	39.02	25.87	22.20	20.78	18.40
IV For C_h = \$150: c = \$15					
1 Load-factor 64.0 per cent	43.30	32.42	29.88	29.25	31.50
2 Load-factor 42.5 per cent	41.35	30.80	28.69	28.17	26.10
3 Load-factor 32.0 per cent	40.07	27.37	23.95	22.73	23.40

Table IX shows that for a hydraulic cost of \$100 and an annual steam cost of \$10, the development must be carried beyond 0.5 sec-ft. per square mile, for any load-factor except the 64 per cent. That is to say, that a development for a stream flow of 0.5 sec-ft., under the assumptions made, can not compete with the steam supply, at any except a very high load-factor. If, however, the annual charges on the steam plant are taken at \$15, then the development of 0.5 sec-ft. is cheaper than the steam plant at all of the load-factors, the point of equal costs being somewhere between 0.25 and 0.5 sec-ft.

If the hydraulic cost is assumed at \$150 and the fixed charges at \$10 then no hydraulic development is economical up to 1.0 sec-ft., with the possible exception of a load-factor of 64 per cent with a development of 1.0 sec-ft. which gives the total cost substantially the same as the steam cost. If, however, the hydraulic cost is taken at \$150, and the annual steam cost at \$15, the combined development might be economical at 1 sec-ft., but not at the low discharges, generally speaking.

The gist of the matter is that on the assumptions made, which

are, as far as I am able to tell, reasonable, the hydraulic development must be carried to a very much higher point of stream-flow than is usually assumed and with a greater percentage of reserve plant, in order that the combined plant shall show any savings in comparison with the steam supply.

These three examples are all for plants with pondage. To show the difference when there is no pondage, Example IV is given, the same general assumptions are made as in Example II, the intermediate load-factor being taken. The cost of the hydraulic plant is taken at $100 per kilowatt of maximum capacity, as in Table II; this corresponds to $100 per kilowatt for a development of

$$Q_m = 0.5/0.45 = 1.18 \text{ sec-ft. as maximum flow.}$$

With these assumptions, Tables X and VII are directly comparable; the difference in total costs is due entirely to the lack of pondage and consequent increased cost of the steam supply. For example, for 0.25 sec-ft., the cost of the steam supply with pondage is $3.20 per kw., without pondage $8.96, making a difference of $5.76 per kw. For 0.75 sec-ft. the difference is $3.94 per kw. The difference in cost increases as the cost of the steam supply increases. The percent-deficiency is calculated from the percent-load curve, in the manner explained above.

EXAMPLE IV: No pondage. Load curve of Fig. 12. Same data as Example II except that C_h = $100 for $Q_1 = 0.5/0.425 = 1.18$ sec-ft. That is, the cost per kilowatt of plant capacity is taken the same, viz. $100, for the same maximum power.

TABLE X.

1. Flow for average power, $Q_m \times f$, sec-ft.	0.25	0.50	0.75
2. Flow for maximum power, Q_m	0.59	1.18	1.77
3. Ratio of capacity, $Q_m/1.18$, =	0.50	1.0	1.50
4. Ratio minimum/maximum-flow, $0.1/Q_m$	0.17	0.085	0.06
5. Steam plant capacity, p_c, $\{1.00 - (4)\}$	0.83	0.915	0.94
6. Per cent-deficiency, p_s	5.80	15.5	25.5
7. $11.40 $\times p_s$	$0.66	$1.77	$2.90
8. $10 $\times p_c$	8.30	9.15	9.40
9 A_s = (7) + (8) = Steam cost	8.96	10.92	12.30
10. A_h = $15 k_r = Hydraulic cost	25.00	15.00	11.70
11. $S = A_s + A_h$ = Total Cost	$33.96	$25.92	$24.00
The increment to be added to line (11) for			
12. C_h = $150 is	$11.70	$7.00	$5.48
13. c = $15 is	4.15	4.58	4.70
And therefore for			
14. C_h = $100 : c = $15, S is	38.11	30.50	28.70
15. C_h = $150 : c = 10, S is	45.66	32.92	29.48
16. C_h = $150 : c = $15, S is	49.81	37.50	34. 18

Example V shows the effect on the total cost of a different division between the fixed and variable portion of the hydraulic cost. The tables above were based on a division of 67 and 33 per cent; but Table XI, for the same data as Example II, assumes a division of 50 and 50 per cent. This change increases the total cost for flows greater than the assumed basic flow of 0.5 sec-ft. and diminishes it for flows less than 0.5 sec-ft.

EXAMPLE V: To show the effect of different ratios of fixed to variable cost of hydraulic plant. Data of Example II, but assuming

$$k_r = 0.5/r + 0.5$$

This change does not in any way affect the steam-reserve costs and is independent of the load curve.

TABLE XI.

1. Q_r, sec-ft.	0.25	0.50	0.75	1.00
2. $Q_r/0.5 = r$	0.5	1.0	1.5	2.0
3. k_r for $a = 0.5$	1.50	1.00	0.83	0.75
4. \$15 k_r for $a = 0.5$	\$22.50	\$15.00	\$12.40	\$11.25
5. \$15 k_r for $a = 0.67$ (Table VII)	25.00	15.00	11.70	10.00
6. Difference (4) − (5)	−2.50	0.0	0.70	1.25
This amount is to be added to the costs of Table VII for C_k = \$100.				
7. For C_k = \$150, there is to be added $\left\{\frac{22}{15} \times (6)\right\}$	−\$3.66	0	\$1.02	1.84

For $Q_r = 0.25$, and all flows less than 0.5, the difference is negative, to be subtracted.

Example VI shows the effect on the annual cost of differences in the hydraulic characteristics of the stream; it gives a comparison between the Potomac, for which the percent deficiency curve is given in Fig. 7 and the Susquehanna, as applied to a load of 64 per cent load-factor. The table shows that the costs for the Potomac are \$1 to \$2 per kilowatt more than the Susquehanna under identical conditions, except in respect to stream flow.

EXAMPLE VI: Conditions of Example I. Applied to the Potomac, as in Fig. 7. The only difference is that for any given flow the deficiency is greater for the Potomac, which means more energy from the steam plant

TABLE XII.

1.	Q_r.....sec-ft.	0.25	0.5	0.75	1.00
2.	Percent-deficiency, Susquehanna, (Fig. 6).....	2.7	10.4	18.1	25.4
3.	Percent-deficiency, Potomac, (Fig.7)	2.7	16.6	28.2	37.8
4.	Difference (3) — (2).....	0	6.2	10.1	12.4
5.	Difference in cost, for Fig. 9.....	0	$1.02	$1.67	$2.05

That is, these sums added to all the cost of Table VI will give the cost for the Potomac, for the same assumptions of costs of plant and operation.

Example VII shows the method of calculating the cost of providing a reserve plant down to different assumed conditions of low discharge. The rated capacity of the development is taken at 0.75 sec-ft. and the total annual cost for a steam plant insuring the delivery down to 0.1, 0.25, and 0.5 sec-ft. respectively is given. This brings out the heavy cost of the steam reserve for the last few per cent of the power deficiency. A difference of $3.10 per kilowatt between the cost for steam plant down to 0.25 sec-ft. and down to 0.1 sec-ft. means a cost of 3.1 cents per kw-hr. for the energy delivered by that portion of the plant necessary to insure this deficiency. It may well be that the penalties incurred by failure to make delivery between these limits would be much less than the cost of insuring it.

EXAMPLE VII: Cost to provide steam reserve for various assumed minimum flows.

Load-curve of Fig. 12: with pondage. Development for $Q_r = 0.75$ sec-ft.

TABLE XIII.

1.	Reserve plant down to flow Q_0 = ...	0.1	0.25	0.5
2.	Ratio, $Q_0/0.75$.....	0.13	0.33	0.67
3.	p_s (Fig. 6).....	0.00	2.7	10.4
4.	p_s for $Q = 0.75$ sec-ft.....	18.1		
5.	Difference (4) — (3).....	18.1	15.5	7.7
6.	p_c, (Fig. 12) for Q_0 /0.75.....	0.63	0.35	0.17
7.	$11.40 × (5) = ...	$2.06	$1.76	$0.88
8.	$10 × p_c (line 6).....	6.30	3.50	1.70
9.	A_s = Cost of steam reserve, (7) + (8).....	$9.36	$5.26	$2.58
10.	A_h, from Table VII.....	11.70	11.70	11.70
11.	Total $A_s + A_h = S$.....	$20.06	$16.96	$14.25

Increased cost to carry reserve down to 0.1 from 0.25. sec-ft.:—
Difference in A_s = $3.10
Energy supplied, 2.7 per cent × 3700 = 100 kw-hr.
Cost per kw-hr., 3.10 cents.

These examples are given merely to illustrate the application of the method to different conditions of stream-flow and load curves. It is not pretended that the results given are applicable generally and the object of the paper is not to give conclusions but simply to develop a method of handling the problem and to give certain illustrations based on reasonable data. I believe that the examples shown will be sufficient to enable any engineer to follow the method substituting the data of his own case for those given. I hope also that I have taken at least one step toward a logical method of procedure for the solution of this problem.

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THE COST OF ELECTRICITY AT THE SOURCE

BY H. M. HOBART

ABSTRACT OF PAPER

The Stott-Gorsuch method is applied to the determination of the cost of manufacturing electricity in a 60-cycle station of 100,000 kilowatts installed capacity. The results correspond to the assumption that such a station is capable of delivering from 350,000,000 to 700,000,000 kelvins per annum for load factors ranging from 0.50 to 1.00. For unity load factor the cost of three-phase electricity at the outgoing cables ranges from 0.65 cent per kelvin with coal at $5.00 per ton, down to a matter of 0.20 cent per kelvin for fuel of negligible cost. A method is indicated for tracing through the increase in the cost of the electricity at later stages of its journey from the source to the consumer.

BY THE time electricity is delivered on the premises of small consumers such considerable costs will have been incurred that the price admitting of any profit can rarely be less than somewhere from two cents to eight cents per kelvin[1]. The original cost of manufacturing in bulk, however, is a far less amount. It is desirable that this should be more generally realized, as it indicates the great field for electricity for large manufacturing enterprises which can be located near the source of electricity supply. Under favorable conditions electricity can be manufactured in bulk at a cost of the order of 0.25 to 0.40 cent per kelvin.

In an address delivered by Ferranti[2] in 1910, the proposition was formulated that, on certain assumptions, a station equipped with ten 25,000-kw. generating sets could be built at a total cost of £7 ($35) per kilowatt. I have made estimates which indicate $35 per kilowatt to be sufficient for a 100,000-kw. station equipped with five 20,000-kw., 1800-rev. per min., steam-turbine-driven, three-phase generators and all the machinery required in such a plant. As a matter of interest it may be stated that the outlay for the turbo-generators, cables, exciters and switchgear is covered by 30 per cent of this $35 per kilowatt. (In and near large

1. In this paper the term kelvin is employed instead of the term kilowatt-hour.

2. *Jour. Inst. Elec. Engrs.*, Vol. 46, pp. 6.

cities this sum would be insufficient, since the outlay for land and buildings would then usually be at least $10 per kw.)

The following estimate for the cost of electricity when manufactured in such a station, will be based on the Stott-Gorsuch method,[3] in accordance with which the total cost is considered as made up of three components. These three components are:

1. Production Costs.
2. Investment Costs.
3. Administration Costs.

I shall divide the Production Costs into two items, A and B.

Item A[4] relates to all components of the Production Costs except fuel. Item B relates to the cost of fuel. While A will vary by a small amount with the load factor, I shall neglect this variation and take:

Item A = $700,000[5]

Item B: In estimating the annual outlay for fuel we must first have data for the over-all efficiency of the station. From an examination of the thermal efficiencies of turbo-generating sets and steam raising plant, one would be led to expect over-all efficiencies from the coal to the outgoing cables ranging from at least 18 per cent for unity load factor down to at least 16 per cent for a load factor of 0.50. But reasoning from the results actually obtained in practise, it is not considered that it would be conservative to take values higher than the following:

Load factor	Over-all efficiency
1.00	15 per cent
0.75	14 " "
0.50	13 " "

Assuming the maximum load from our 100,000-kw. station to be 80,000 kw., the annual output for these three cases is:

Load factor	Annual output in mega-kelvins.
1.00	700.
0.75	525.
0.50	350.

3. TRANS. A. I. E. E., Vol. XXXII, 1913, p. 1619.

4. Item A covers wages, repairs, lubricants, water, supplies, etc.

5. It is believed that an analysis will show this value to be reasonably representative for Item A and that in so far as it errs it is in the direction of being conservative. It will cover any investment costs associated with the water supply, such as cooling towers when required.

The energy in the coal consumed per annum amounts to:

Load factor	Mega-kelvins of energy in the coal
1.00	4660.
0.75	3750.
0.50	2690.

The estimates may be based on coal with a calorific value of 12,000 B.t.u. per pound.[6]

1 kelvin equals 3411 B.t.u. Consequently each (2000-lb.) ton of coal contains

$$\frac{12{,}000}{3411} \times 2000 = 7000 \text{ kelvins}$$

The quantity of coal burned per annum is as follows:

Load factor	Quantity of coal burned per annum
1.00	667,000 tons
0.75	535,000 "
0.50	384,000 "

In the following table are set forth the outlays for fuel on the basis of 50 cents per ton and $5 per ton.

Load factor	Annual Outlay for Fuel	
	50 cents per ton	$5 per ton
1.00	$334,000	$3,340,000
0.75	268,000	2,680,000
0.50	192,000	1,920,000

The above amount represents Item B, the fuel component of the Production Costs per annum. We have already stated that for the remaining component of the Production Costs, (Item A), we shall take the constant value of $700,000.

6. The results of this investigation are presented in such form as to permit of ready modification to correspond to the use of fuel of other calorific values than 12,000 B.t.u. per pound.

Adding A and B we obtain the total Production Costs set forth in the following table.

Load Factor	Production Costs per Annum.	
	Fuel at 50 cts. per ton	Fuel at $5 per ton
1.00	$1,034,000	$4,040,000
0.75	968,000	3,380,000
0.50	892,000	2,620,000

In terms of cents per kelvin, the above Production Costs are:

Load Factor	Production Costs per kelvin	
	Coal at 50 cts. per ton	Coal at $5 per ton
1.00	0.148 cent	0.576 cent
0.75	0.184 "	0.645 "
0.50	0.254 "	0.750 "

We now come to the second component of the total cost, namely the Investment Costs. At $35 per kilowatt the initial cost of the 100,000-kw. station is:

$3,500,000.

This is sufficient to cover engineering supervision and contingencies.

On the basis of:

Interest	5.0 per cent
Rates, taxes and insurance	3.0 per cent
Amortization	4.6 per cent
Total annual charges on investment[7]	12.6 per cent

we arrive at an Investment Cost per annum of

$$0.126 \times 3{,}500{,}000 = \$441{,}000.$$

In terms of cents per kelvin the Investment Costs are:

Load factor	Investment costs per kelvin
1.00	0.063 cent
0.75	0.084 "
0.50	0.126 "

7. For other capital costs per kw. and for other rates and other depreciation assumptions the corresponding annual investment costs are readily deduced. Those adopted in this investigation would appear representative for such a station.

As to the final item in the total cost, namely the Administration Costs, let us distinctly limit this item to the bulk manufacturing undertaking. Let the *marketing* of the electricity be separately handled by another undertaking. With this understanding, an allowance of $100,000 per annum is reasonable for the Administration Costs. This provides for an administrative organization simply concerning itself with manufacturing the electricity and delivering it at the outgoing cables.

Per kelvin, this amounts to:

Load Factor	Administration Costs per kelvin
1.00	0.014 cent
0.75	0.019 "
0.50	0.029 "

The Total Costs are worked out in the following table, in which Production Costs are indicated by I, Investment Costs by II, and Administration Costs by III.

Load Factor	Component and Total Costs in Cents per kelvin	
	Coal at 50 cents per ton	Coal at $5 per ton
1.00	I = 0.148 cent II = 0.063 " III = 0.014 " Total = 0.225 cent	I = 0.576 cent II = 0.063 " III = 0.014 " Total = 0.653 cent
0.75	I = 0.184 cent II = 0.084 " III = 0.019 " Total = 0.287 cent	I = 0.645 cent II = 0.084 " III = 0.019 " Total = 0.748 cent
0.50	I = 0.254 cent II = 0.126 " III = 0.029 " Total = 0.409 cent	I = 0.750 cent II = 0.126 " III = 0.029 " Total = 0.905 cent

These total costs are plotted in Fig. 1 with cost of coal as abscissas. They are plotted in Fig. 2 with load factors as abscissas.

For water power stations, if there is no charge for the water, and if the total investment can be kept as low as $35 per kilowatt, the lowest curve in Fig. 2, (*i.e.* the curve for fuel at a negligible cost per ton) may be taken as affording a fair indication of the cost of electricity at the source.

This investigation has been based on the assumption that the electricity delivered from the station is of unity power factor. For lower power factors the total cost of the electricity will be higher. Professor Arno of Italy has devoted a great deal of study to the influence of the power factor on the cost of electricity and has arrived at the conclusion that for practical purposes the cost may be taken as proportional to two-thirds of the true output, plus one-third of the apparent output (*i.e.*, the true output divided by the power factor). Thus if we take the case of our 100,000-kw. station when the load factor is 0.50, we have seen that the cost, with coal at 50 cents per ton, is

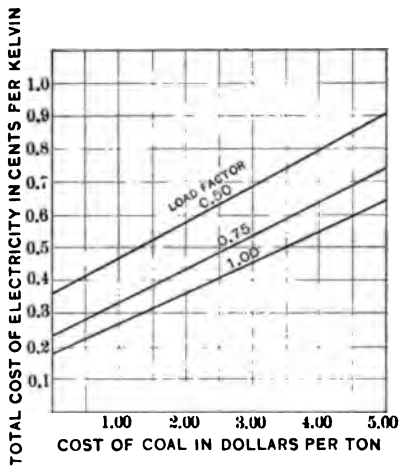

FIG. 1

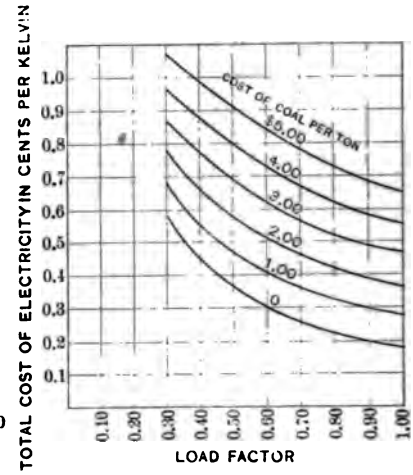

FIG. 2

0.409 cents per kelvin for unity power factor. If the load is of 0.80 power factor the cost by the Arno rule will be:

$$\left(0.667 + \frac{0.333}{0.80}\right) \times 0.409 = 0.444 \text{ cent per kelvin}$$

Prof. Arno's rule may be regarded as a useful approximation for representative conditions. The application of the present method of analysis to outputs of different power factors would show that no such simple rule would suffice. The influence of the power factor would for instance be much affected by the ratio of the cost of fuel to the total costs, and would be different with different load factors.

Indeed, a similar general criticism applies to Mr. Stott's nevertheless useful approximate rule that the Production Costs may be taken as inversely proportional to the fourth root of the load factor. There may be wide deviations from such a rule occasioned by extremes in cost of fuel and in other conditions.

Furthermore the costs which we have worked out have related to delivering 60-cycle three-phase electricity at the pressure at which it is generated, say 10,000 volts. If it is to be stepped up to, say, 100,000 volts, to be transmitted in bulk to a distance, then the cost at the high-pressure side of the step-up transformers may be obtained as follows:

Let us take the case of a load factor of 0.50 and coal at 50 cents per ton. Let the power factor be unity. The cost under these conditions has been estimated to be 0.409 cent per kelvin. We shall require to provide step-up transformers with an aggregate capacity of 100,000 kw. Their cost would be of the order of $2.70 per kilowatt, making a total outlay of $270,000. The annual outlay for interest, rates, taxes, insurance, amortization, repairs and attendance may be taken as

$$0.15 \times 270{,}000 = \$40{,}500.$$

The annual output from the station when the load factor is 0.50 has already been estimated to be

350 mega-kelvins.

Taking the annual over-all efficiency of the transformers as 97.5 per cent, the output from the transformers is

$$350 \times 0.975 = 341.5 \text{ kelvins.}$$

Therefore the step-up transformer costs, per kelvin delivered from them, are

$$\frac{4{,}050{,}000}{341{,}500{,}000} = 0.012 \text{ cent}$$

The total cost per kelvin delivered from the step-up transformers is

$$\frac{350.0}{341.5} \times 0.409 + 0.012 =$$

$$0.419 + 0.012 = 0.431 \text{ cent.}$$

Thus the cost has increased 5.5 per cent by the time the pressure has been stepped up. This paper is entitled " The Cost of Elec-

tricity at the Source." By similar processes, however, the increases in cost can be traced right through to the consumers' premises.[8] But the reasoning becomes very involved when we arrive at the stages where the electricity is no longer carried in bulk. At these stages questions relating to appraisements of value, diversity factor, ethics and commendable sentiment render it impossible to arrive at any precise method which can be conclusively demonstrated to provide for equitably distributing the total costs amongst the various consumers.

8. In a paper entitled "The Relative Costs and Operating Efficiencies of Polyphase and Single-Phase Generating and Transmitting Systems," Hobart, TRANS. A. I. E. E., Vol. XXXI, 1912, p. 115, the author has applied this method of studying in a certain case the growth of the cost of electricity, commencing with the outgoing cables from the generating station and concluding with the cost as delivered from the distant substations.

DISCUSSION ON "THE COST OF ELECTRICITY AT THE SOURCE" (HOBART), NEW YORK, FEBRUARY 26, 1914.

J. W. Lieb, Jr: I am sure that under the conditions obtaining in our larger cities the figure given by the author, of $35 per kilowatt of capacity, will not cover the real estate and buildings of a character to satisfy local conditions. The sum of $35, even if otherwise adequate, which I doubt, would allow the merest shell of a building rather than such a structure as it would be necessary to provide to house a plant of the capacity indicated by the author.

H. R. Summerhayes: I ask Mr. Hobart how many days' coal storage is provided for under his plan. In these days of coal strikes and interruptions to transportation it seems necessary to provide a large acreage of land to store a large amount of coal. Such a station ought to require quite a large area for that purpose.

H. W. Buck: There is one advantage which the steam plant has in this comparison. As a rule, the water power plant is many miles from the point at which the power is applied, and the cost of transmission lines, substations, etc., must be added. On the other hand, the steam plant, as a rule, can be located practically at will, and as near as possible to the center of load. This also applies to operating costs on the transmission system, which the steam plant will not have to so great an extent.

Frederick A. Scheffler: I hope that the author of this paper will be more specific in giving us exact data as to how he arrives at $35 per kilowatt for the cost of constructing a complete 100,000-kw. station.

I would like to know what size boiler units he proposes to use, whether he will use steam turbines, and if so, what size units, working steam pressure, superheaters, if any, and degree of superheat, at what rating the boilers will be operated and what kind of stokers will be used, whether under-feed or otherwise, and whether the cost covers economizers.

I have in mind a plant which is being constructed in the West at the present time, of an ultimate capacity of 120,000 kw. The company which is building this plant feels that if it can construct the station, using six 20,000-kw. turbines and twelve 2400-h.p. (nominal rating) boiler units, with superheaters for 200 deg., and operating the boilers at 200 per cent of rating when necessary, and the cost does not exceed $55 per kilowatt complete, it will have a very reasonable and inexpensive station, considering its construction, which is to be of the very best throughout.

H. L. Wallau: I have only one criticism to make of this paper, and that is the figure of $35 per kilowatt. That figure has been qualified in this discussion, and it has been qualified as presented by Mr. Hobart. However, in a city such as Cleveland is, the tendency will be for the engineers of the municipality to say, just as soon as a figure of $35 per kilo-

watt is published in an Institute paper, that it must be pretty close to the actual cost. Apparently the way they figure cost in Cleveland in a municipal undertaking, is to take the figures, for instance, published in the Institute PROCEEDINGS for a 300,000-kw. plant, and say, "If they can do that in a 300,000-kw. plant we ought to be able to do practically that in our 15,000-kw. plant", and as a result they have published a schedule of rates, with a maximum rate of three cents and a minimum rate of one cent. I believe on last Tuesday they got ready to pass a maximum rate ordinance of three cents, to which they expect us to conform. I think for these reasons, when a statement is made, and a figure is published, that it should be carefully qualified, because the tendency towards municipal ownership is growing rapidly in this country, and the analysts are, I believe, making some very grave errors in their calculations.

H. B. Alverson: The load factors given are too high for the usual existing conditions, and while it may not be the intention in the paper to give exact figures, I believe the load factor which will occur in practise will be nearer to 35 or 40 per cent than to 50 per cent. In such cases the cost per kilowatt-hour would rise somewhat higher in proportion than the figures given. Without going into the calculation of the proportion of costs based on the load factor, I think the average experience is that it is very much higher than that which is given in the paper.

O. K. Harlan: Regarding the matter of depreciation, it might be of interest to note that a few weeks ago, before the American Society of Heating and Ventilating Engineers, a paper was presented giving something of the life history of quite a number of the old electric lighting steam-driven plants in this city, and the matter of depreciation was dealt with in that paper. It traces the history of the very earliest installations, including the first steam-driven electric dynamos which were operated in the city. One of the old ones is in the Mills building, and a number of others are down-town, near it. The depreciation was shown to be quite a variable factor; of course, some generators will deteriorate faster than others, and the matter of economy and efficiency is quite an item also; that is to say, some of the more recent generators may be of so much higher efficiency that it is worth while to discard a really good working machine in order to put in a more modern machine of higher efficiency. However, this paper shows that a number of these earlier plants have had a useful life of twenty years; some are really working today, which were installed twenty years ago—but the matter of depreciation, while it is a very interesting subject, is really somewhat intricate, and there are a good many factors entering into the final decision.

H. C. Abell: If Mr. Hobart means the $35 to cover the cost of machinery, water facilities for a plant of that size, storage requirements, working capital, supplies, cost of financing the undertaking, and all the incidental expense, I think unquestionably he used the wrong multiplying factor to arrive at the figure given, which I consider too low.

Another thing which attracts one's attention is the five per cent interest figure used by Mr. Hobart. I do not know of any money source which could be induced to provide funds for a power-generating plant on a five per cent basis.

I suppose amortization placed at 4.6 per cent is a depreciation fund, for a power plant is usually not amortized, but is a continuous business where the owners have to provide funds continuously for new construction after the plant once starts. Amortization is entirely different from depreciation; the two terms should not be confounded.

A. H. Kruesi: With regard to depreciation, I believe obsolescence often cuts a much larger figure than depreciation due to wear and tear. I am associated with a large steam-turbine power plant built eleven years ago. The stokers and their auxiliary equipment are now being scrapped because they are obsolete, though not worn-out. A number of boilers installed seven years ago are also being scrapped because they are of a type no longer manufactured and the allowable working pressure has been reduced, so that they have become unsuitable to their purpose. The entire switching equipment is being replaced after eleven years' use because the plant has grown and it is no longer adequate for the amount of power behind it. I agree with the criticism of Mr. Hobart's paper, on the score of his capital cost charges. I do not see how they could possibly be figured at less than 15 per cent.

V. Karapetoff: Mr. Hobart's paper has been criticised on account of the specific numerical data given in it. I know from certain experiences in court testimony that outsiders are only too liable to ascribe to the Institute any data published in its PROCEEDINGS, in spite of the well-known fact that the Institute is not responsible for opinions expressed by its individual members. To me, personally, Mr. Hobart's paper is exceedingly interesting and instructive in giving a concrete method of calculation. If he had chosen to use letters, instead of numerical values, I am afraid the paper would be exceedingly difficult to follow, but then it would have been of greater general interest, as any one could substitute numerical values for his particular problem and the above criticism would be obviated.

I was surprised at the statement that the outlay for the turbo-generators, cables, exciters, switch gear, etc., amounts to only 30 per cent of the total cost of the generating station. It seems to me that engineers in this country ought to be more interested in the Thury system of generation, which, so far, has been mainly applied to hydroelectric stations, but lately was chosen in London for underground distribution from a steam plant. The principal advantage of the Thury system is that not only the cables themselves cost much less, but also the generating station is lower in cost; while the generators themselves are more expensive, the cost of auxiliary apparatus is much lower. If one goes into a station like the Northwestern station in Chicago, it is the auxil-

iaries which strike one's eye, and it is the auxiliaries which occupy the most room and apparently seem to cost the most.

G. L. Knight (by letter): The author of this paper states that a 100,000-kw. steam station, consisting of five 20,000-kw., 60-cycle, 1800-rev. per min., three-phase turbo-generators, together with all the apparatus, both steam and electric, required for the operation of such a plant, can be built in this country for an over-all charge of $35 per kilowatt.

This paper, being presented before the A. I. E. E., presupposes in the absence of contrary statement that the figures given represent American practise, but in replying to the discussion on his paper in the meeting of February 26, Mr. Hobart defended his estimate by the following figures taken from estimates of plants constructed in England:

Turbo-generators, including exciters and switch gear	$10.50 per kw.
Steam raising plant	8.50 " "
Condensing equipment	5.00 " "
Building	8.00 " "
	$32.00 per kw.

This leaves only $3.00 for the rest of the charges, which must include land, general engineering and construction expense other than that included in the items as given, also all overhead charges during the construction period.

In place of the figures set down by Mr. Hobart, I would give the following as minimum values, and while they will vary greatly according to the conditions a plant must meet, the total cost per kilowatt will be often much nearer $75.00 than the figure given.

Building		$10.00	
Turbo-generators, including exciters.	$12.50		
Switch gear	3.00		
		15.50	
Steam plant			
Boilers	6.00		
Stokers	2.50		
Flues and piping	2.00		
Coal and ash handling equipment	1.50		
		12.00	
Condensing equipment			
Condensers and pumps	3.00		
Condensing tunnels	2.00		
		5.00	
Engineering, drawings, supervision			42.50
and other overhead expenses, 15 per cent			6.35
Allowance for piecemeal construction and contingencies, 15 per cent			6.35
			$55.20

To those of us in the employ of public service companies this paper seems at least ill-advised. Regulating bodies and the advocates of municipal ownership are constantly challenging our capital costs, and when a company's books show a cost of $50 to $75 per kilowatt for a new plant (and older ones will be even higher), papers such as this are quoted in attempts to prove such costs excessive.

In such cases it is assumed, by those who do not know the Institute rule, that having accepted such a paper for presentation at a meeting, the Institute must have passed on it as being reasonable.

I think Mr. Hobart should have stated that his whole case rested on English figures, and I am inclined to believe that even in England no plant has ever been completed which, when all charges were accounted for, came within his figure at $35 per kilowatt.

Frederick G. Strong (by letter): Permit me to say a word in behalf of our water powers; they seem to have very few friends among those who have discussed Mr. Hobart's paper.

I remember a paper by Dr. Emory, in which the general statement was made that where the cost of water power development exceeded $150 per horse power a steam-driven plant would be advisable where good coal could be obtained at about $4 per ton. We have heard, periodically, that a slight increase in efficiency or a slight decrease in the cost of steam-driven machinery, would cause the water powers to be abandoned, or left undeveloped.

We have seen a marked increase in steam efficiency in the past ten years and a marked decrease in cost per kilowatt, due to increased size of units and increased speed and activity of material, but the water powers are still in use. None have been abandoned, and plans are being formulated for the development of many more.

The theory that water powers should be abandoned, or left undeveloped when they show a greater cost than equivalent steam-driven stations, does not seem correct, and I believe the time is not far distant when we will develop every available water power, to the end that the coal supply may be conserved as much as possible.

Undoubtedly the water powers at Holyoke, and Lowell, and Lawrence, and Manchester have cost far more than equivalent steam power, but if those investments were annihilated, does any one believe that the power would be left undeveloped?

In the energy of falling water Nature has not by any means given us something for nothing, but it is doubtful if we may expect a nearer approach.

H. M. Hobart (by letter): I shall deal with the contributions to the discussion of my paper in the order in which they were made.

As to the first comments which were made by Mr. Lieb, it

would appear that his intention is to supplement my paper and emphasize the importance that it should not be construed as applying to stations located in or near large cities. It was clearly shown in my paper that I referred to a station located with especial reference to low cost of land, abundance of circulating water and low price for fuel. This necessarily locates the station at some situation where architectural effect is absolutely out of place. In the recent report made to the London County Council by Messrs. Merz and McLellan, it is pointed out that in modern plants "the power house tends more and more to become a metal structure for housing the machinery rather than an actual building in the usual sense." The savings which can be effected under the conditions which I describe for my plant are inapplicable to a power house located in our larger cities, and I am glad that Mr. Lieb took the occasion to emphasize this point. Furthermore, in city plants supplying electricity for all sorts of purposes to a large community there must be large investments for duplicate switch equipments and for supplying large numbers of feeders. This inevitably runs up the cost, as it does also the need for economizers, which are justifiable under these circumstances, since the price of fuel is relatively high. It was expressly stated in my paper that no outlay for transformers was included, and further, that the estimates related to 60-cycle generating sets. These sets were only five in number, of the most modern type, and were for a rated speed of 1800 rev. per min. In city stations it is often necessary to supply, not only 60-cycle electricity, but also 25-cycle electricity, and furthermore, the stations will usually be found to be equipped with more than one size of generator. Moreover, the average rating of all the generators in the station is usually much below that of the 20,000-kv-a. units on which I based my estimates, and they are driven at lower speeds, as a consequence of which they are larger, more expensive in first cost, more wasteful of fuel, and a greater outlay is required for the attendance upon them. When a given aggregate output is delivered from ten small units, as against five large units, the outlay for wages in the station is decidedly greater. Mr. Lieb considers that the real estate and buildings for a station in our larger cities would not be covered by $35 per kilowatt of capacity. Taking it at $40, and including an appropriate allowance for the increased outlay for switch gear and for economizers and transformers, then, with an allowance for engineering and contingencies amounting to 10 per cent of the total, we arrive at over twice the capital outlay per kilowatt installed that would have been necessary on the same scale of prices for a station complying with the conditions set forth in my paper.

In the matter of Mr. Summerhayes's suggestion that in these days of coal strikes and interruptions to transportation, it seems necessary to provide a large acreage of land to store a large amount of coal, I would point out that with such locations as that clearly contemplated in my paper, the land could not rea-

sonably be taken as costing more than $200 per acre. On this basis, the outlay for a site of 50 acres would only amount to $10,000, which is less than three-tenths of one per cent of the total capital outlay for this 100,000-kw. generating station. Mr. Summerhayes evidently also had in mind the conditions in large cities, far away from the mines, and I quite agree with him that under these conditions the point which he mentions would be one requiring careful attention.

I fully agree with the point which Mr. Buck makes that the steam plant has the advantage over the waterpower plant, that it may sometimes be located quite near to the center of the load, thus minimizing the costs in transmitting the electricity to the customers. However, I dealt with "The Cost of Electricity *at the Source*" and pointed out that by locating a generating station where the conditions as regards fuel and water supply and cost of land are favorable, electricity can be manufactured for a low price and that industries, the cost of whose product depends largely on the outlay for electricity, would be well advised to realize and take advantage of such possibilities.

I am pleased to be able to comply with Mr. Scheffler's request for more specific data as to how I arrive at the cost of the complete 100,000-kw. station. This is set forth in the following table:

	Five 20,000-kw. units
I—Turbo-generators, exciters, cables and switch gear, but exclusive of step-up transformers	$10.50
II—Boilers, superheaters, furnaces, and stokers, but exclusive of economizers, pumps and piping	9.00
III—Condensers, exclusive of pumps, piping and tunnels	2.50
IV—Pumps, piping, tunnels, valves and traps	1.50
V—Land and all buildings and structures, including machinery foundations, stacks, bunkers and conveyers	8.00
VI—Engineering and contingencies (10 per cent)	3.50
Total cost per kilowatt	$35.00

Mr. Wallau also points out how important it is that the conditions under which such figures can be reached should be clearly stated. I welcome Mr. Wallau's assistance in helping me to point out the distinction between plants of the size and character which I am discussing in the paper, and such relatively small plants as those to which he refers.

Regarding Mr. Alverson's comments, I show in the curves in Fig. 2, on page 396, the cost of electricity for all load factors down to 0.30. It may, however, be of interest to point out that the application of electricity to chemical and certain other industries often permits of much higher load factors than have, until recently, been at all customary, and that decided commercial importance attaches to a knowledge of the costs under such conditions of high load factor. Such applications are usually only practicable when the cost of electricity is very low, and in the

near future we shall certainly see such industries purposely located where conditions are favorable as regards plentifulness of water and low cost of fuel and land.

Mr. Harlan makes some interesting suggestions. He calls attention to 20 years as a reasonable life for electrical machinery in many cases. My figures for the investment cost are based on an equivalent life of 15 years.

The next two contributors to the discussion of my paper were Messrs. Abell and Kruesi. It is the opinion of both of these gentlemen that my investment costs are a little too low, Mr. Abell's criticism being that funds can rarely be obtained for a power generating plant at so low a rate of interest as five per cent, and Mr. Kruesi emphasizing the importance of the obsolescence factor. All engineers realize the difficulty of equitably assessing the investment costs, owing to the impossibility of predetermining the obsolescence factor and the great difference in the financial standing of companies embarking upon electricity supply enterprises. I believe that the figures on which I have based the annual investment charges are representative for the case under discussion, but it is obviously important to apply a safety factor which should be inversely proportional to the financial standing of the companies.

I am interested in Prof. Karapetoff's suggestion that my paper would have been of greater general interest had I chosen to employ letters instead of numerical values. My own experience is, however, that the paper would not have attracted attention. It is my experience that papers rarely fulfil any useful mission unless they stimulate discussion.

Mr. Knight puts forward an interesting alternative estimate, regarding which I should like to offer the following comments. For " turbo-generators, including exciters," Mr. Knight allows $12.50 per kilowatt. For " turbo-generators, exciters, cables, and switch gear " I gave the figure of $10.50 per kilowatt. For a city station with its more elaborate provision for switch gear and its large number of feeders, the equivalent allowance would be $11.50 per kilowatt were five 20,000-kw., 60-cycle, 1800-rev. per min., unity power factor turbo-generators to constitute the equipment. If we turn to Fig. 17 in Messrs. Stott, Pigott and Gorsuch's paper* entitled *Present Status of Prime Movers*, presented at the Detroit Convention, June, 1914, we find $7.50 per kilowatt taken as the " average " cost of a 20,000-kw., 60-cycle, 1800-rev. per min. turbo-generator. This would seem to indicate that my figures are conservative for large plants favorably located.

As regards the other items, Mr. Knight's estimates do not differ materially from my own, except that he allows 30 per cent for "engineering, drawings, supervision and other overhead expenses, piece-meal construction and contingencies " as against my allowance of 10 per cent for " engineering and contingencies." I quite agree that such items may run up to large values and that for each case they must be separately considered.

*See Part II of this volume of TRANSACTIONS.

The last contribution to the discussion is by Mr. Strong and is to the effect that waterpower should—and will—be developed irrespective of the relative capital and operating costs of the investment, as compared with the equivalent undertaking employing turbo-driven generators. One of the objects which I had in view in writing my paper was to call attention to the liability of misapplication of capital. Large amounts are often invested in waterpower developments running much above $100 per kilowatt installed and in some of these cases it could be demonstrated that the greater capital charges more than offset the elimination of fuel costs. Often a steam-turbine station at a favorable site would represent a better investment. But there is the liability that any consideration of a steam-turbine station will be dismissed after very superficial calculations, in the mistaken belief that the investment for the steam station will necessarily be excessive. Fifteen years ago (before the advent of the steam turbine) the case was much more favorable for waterpower as compared with steam.

It is equally desirable to call attention to the related danger that the high efficiency of the internal combustion engine will attract capital, notwithstanding that the generating sets alone will cost at least $60 per kilowatt and even the fuel cost will be as great with the internal-combustion engine as with the steam turbine with oil at 2½ cents per gallon and coal at $3.00 per ton.* The outlay for attendance, lubrication, and repairs will be much greater with the internal combustion installation. The misdirection of capital in this way would be checked by the more general realization of the low investment cost associated with steam turbines.

In conclusion I should like to take the opportunity to discuss briefly the factors which have contributed to the rapid progress which has been made toward decreased cost of electricity. There has been of recent years rapid progress in the direction of increased efficiency of prime movers. This has been accelerated by the use of individual sets of very large capacity. Not only have these sets relatively high efficiencies, but the investment cost per kilowatt is relatively low. It is well known that the steam consumption of modern steam tubines is much less than ten years ago, consequently a given capacity of steam raising and condensing plant will now provide steam for a station of much greater capacity than formerly. The methods of firing steam boilers have simultaneously undergone radical changes, so that in addition to the lower investment cost, due to the decreased total capacity of steam raising plant required, there is the further investment gain due to the more intense utilization of the plant. In view of these considerations, there will be no difficulty in realizing that a given outlay for buildings and machinery will

*This is explained in my paper entitled "The Cost of Manufacturing Electricity", page 617 of the *General Electric Review* for September, 1913.

be adequate for delivering much more electricity per annum than formerly.

At the same time it must be recognized that in and near large cities there has been a counteracting tendency to require much finer buildings with much greater attention to architectural effect, and since, as Mr. Lieb has pointed out, the cost of land and buildings may easily be the largest item for such undertakings, any lower investment cost per kilowatt for machinery permits of a much less percentage decrease in the total cost than is obtained in the case of such plants as those to which my paper had specific reference. My paper dealt exclusively with plants of enormous capacity (in this case 100,000 kw.) located under such conditions that the outlay for machinery constitutes much the largest item. Under such circumstances the contrast between a modern plant equipped with machinery purchased at modern prices and the best plant which could be put down ten years ago and which would be of much smaller total capacity, owing to the then relatively small demand for electricity, is marked.

It should, in conclusion, again be emphasized strongly that my estimates do not apply to plants located in or near large cities. On the first page of my paper I called attention to "the great field for electricity for large manufacturing enterprises which can be located near the source of electricity supply." I expressly stated that my costs applied to the manufacture of electricity " in bulk " and " under favorable conditions " and I was very precise in pointing out that my costs did not apply to electricity manufactured in and near large cities.

resented at the 2nd Midwinter Convention of the American Institute of Electrical Engineers, New York, February 27, 1914. Under the auspices of the Electric Power Committee.

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DISTRIBUTION OF ELECTRICAL ENERGY

REPORT OF SUB-COMMITTEE ON DISTRIBUTION

P. JUNKERSFELD, CHAIRMAN

IN THIS report your committee has submitted an outline of what it believes to be good engineering practise in the distribution of electrical energy for various purposes and under various conditions, which outline it is hoped will encourage and direct further attention to this vitally important matter.

The distribution of electrical energy in a given area, like the distribution of any raw or manufactured product, any commodity or utility, depends fundamentally upon the density or number of points of consumption or of use within the particular area. Other things being equal, any given method of distributing electrical energy should afford better results, reliability and economy, in the denser of two equal areas.

In practise, all other conditions, as well as areas, vary widely, because electrical energy is used for so many different purposes and in such rapidly increasing quantities. Electrical energy should be distributed in such form and at such voltage as will produce the best final result, all things considered, and each given proper weight. A full consideration of best final result immediately involves economic questions beyond the limits of this report, including the generation of electrical energy for practically every purpose by interconnected power houses under unified operation. The advantage of unified operation of power houses has, however, been thoroughly demonstrated and is quite generally recognized in this country and abroad. In all such cases most of the electrical energy required in a given area or community is usually generated in relatively large economical power houses and, to secure the best result in distribution, in such form as will best lend itself to meet the predominating demand in that community.

Such unified operation or centralized generation of electrical energy has so far usually been limited to power houses, and in

some cases includes the transmission to substations. In a few cases this centralization has recently been carried a step further to include the substation. In one of these cases, very large amounts of electrical energy had been supplied by the electric power company to each of two competing metropolitan railway systems, one elevated and the other operating on the street surface, both serving the same territory (the north and west sides of Chicago) and each operating its own substations independent of the other railway system. Supplementary contracts have recently been made under which the power company leased all of the substations of the elevated railway system and then contracted to exchange conversion service with the surface railway system. The power company also agreed, with necessary limitations, to build new substations where needed to deliver 600-volt direct-current energy to either of the above two systems.

As a result, the elevated railway system in this territory will be supplied very soon from 13 distributing substations instead of seven as formerly, and the surface railway system in this territory from 18 distributing substations instead of 10 as formerly. The average feeding distances are thus even at the start almost cut in half and make possible very large savings in distribution. Four of the additional substations are owned by the power company and will be also used for distribution of electrical energy to its general lighting and power customers, thus making a further saving in distribution investment and operating expense in that community.

In one of the cases above mentioned, a single substation with 4000-kw. synchronous converters supplies 600-volt direct current to three different railway systems, where under former methods three separate small substations would have been necessary. In another, direct current at 250 volts to a three-wire Edison system and at 600 volts to surface railway systems, is delivered from one substation instead of two. In both cases the investment in high-tension cables from the power house, in substation land, building and equipment, was about one-half what it would have been if the two or three separate substations had been built in each case. This reduction in investment results from: (1) less reserve high-tension cable; (2) less land and building for one large substation than for two or three small ones; (3) less cost per unit of substation equipment because of larger units; (4) less cost per unit of demand in kilo-

watts on one substation than on two or three, because of considerably lesser amount of spare capacity in kilowatts to give equally reliable service.

The operating expense for the one large substation was practically no more than the operating expenses for each of the two or three small ones, thus reducing these expenses one-third and one-half, respectively, in the two substations referred to.

In the above cases the high-tension supply to the substations was all at 25 cycles. Almost the same possibilities for economy exist in many cities where the general supply is at 60 cycles, as 60-cycle synchronous converters have now been developed to a point where in all except possibly the very largest units they are comparable with 25-cycle synchronous converters.

This tendency toward utilizing as many substations as possible for distributing all electrical energy (of whatever form or voltage) required within the economical radius of each substation, must result in large savings in future. Especially is this true when we realize that today only about one family out of four in this particular territory of rapidly growing population is enjoying the use of electric service. The possibilities in demand for electrical energy in transportation and industrial work in this particular territory seem equally promising.

The great importance of the subject of distribution of electrical energy is further indicated by the fact that in the average centralization system in a large city the fixed charges and operating expense of the distribution system are nearly three times the fixed charge and operating expense of the power house. This includes all equipment and conductors between power house switch gear and the customers' premises and refers to kilowatt-hours sold for general light and power, exclusive of bulk supply.

All expenditures of every kind for electrical energy for every purpose in any community should be viewed from the standpoint of such community, because that community in the end reaps most of the benefits, if any, and suffers most of the losses, if any, that result from the particular manner in which electrical energy is generated and distributed in such community. The advantage of centralization in generation of electrical energy is generally recognized, but the advantage of some centralization in transmission and in the substations is not so well understood.

In addition to the centralization of electric power generation, the centralization of distribution, at least the transmission to substations and the conversion therein, should always receive the most careful consideration.

The use of a single substation building for distributing electrical energy reliably and economically for general lighting and power, for surface railways and for elevated railway trains, has already been demonstrated. It is only a small step farther to distribute 600-volt direct current for steam railroad terminal operation from the same substation. If necessary, 1200-volt instead of 600-volt direct current could be distributed from the same substation and still effect a considerable saving if enough foresight and breadth of view is exercised by all parties interested.

Beyond the substation it is also very desirable to have centralization, at least to the extent of a single system for all general supply. The wastefulness of two different systems of mains for general supply overlapping in the same area, is quite generally appreciated. Different systems have, however, been well standardized for different conditions as, for instance, the Edison three-wire system for the denser portions or business districts of large cities, and the alternating system for practically all other general supply. In addition, there are various problems in distribution that are peculiar to the particular purpose for which the electrical energy is used.

In the following sections several of the most important problems in the distribution of electrical energy have been treated by members of the Committee who have had particular experience in these problems, which are as follows:

Three-wire d-c. distribution, by P. Torchio.

Alternating-current distribution, by H. B. Gear.

The relation of consumers' apparatus and wiring to distribution, by H. Goodwin.

D-c. distribution for surface lines, urban service, by R. H. Rice.

D-c. distribution for underground and elevated railways, by E. J. Blair.

D-c. distribution for interurban and steam railroads, by W. G. Carlton.

A-c. distribution for interurban and steam railroads, by W. S. Murray.

The relation of distribution problems and switching equipment, by E. B. Merriam.

Distribution for street lighting service, by P. M. Lincoln.

This report, including the sections and references therein to other contributions on the distribution of electrical energy, is supplemented by a list of references to such contributions from American and foreign authors as have been put into book form or have not been presented before the American Institute of Electrical Engineers. This list of references on the subject of distribution of electrical energy it is hoped will supplement to some extent the recently published Index to the TRANSACTIONS of the American Institute of Electrical Engineers—1884 to 1910 inclusive.

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APPENDIX I. THREE-WIRE D-C. DISTRIBUTION

BY PHILIP TORCHIO

The modern three-wire d-c. distributing systems consist essentially of a three-wire network of distributing mains fed by a multiplicity of cable feeders delivering current at different points of the network of mains, and a system of substations supplying the current to the feeders.

With the exception of the former low-tension d-c. generating stations, which have been replaced by the modern substations receiving high-tension alternating current and transforming it into low-tension direct current, the complete three-wire distributing network of over 25 years ago is still giving in every respect its full 100 per cent service alongside of all subsequent additions. This is almost a unique instance of permanency of usefulness of electrical apparatus used by central stations.

FEEDERS AND MAINS

The current was formerly distributed underground by Edison tube feeders, but in the last 15 or 20 years the cable system has superseded the former tube systems. For feeders, concentric cables with pressure wires are often used, they being either armored and laid in the ground, as is done mostly abroad, or being drawn into subway ducts, as in this country. In other cases single-conductor cables are used with pressure wires in the main cables or separate pressure wires outside. The network of mains consists of three single-conductor cables, of equal copper cross-section, drawn in distributing ducts in the

streets near the curb line or sometimes under the sidewalk. This system of mains is interconnected at each street crossing, thereby making a solid meshed system. Feeders, which are laid from the station to a number of suitable points, end at a junction box into which enter the feeder cable and pressure wires, and from which issue the main cables tying to the network of mains meeting at that intersection of the street. The junction box may be installed in the manhole or just outside in the street. The neutral main cables are spliced together and grounded at frequent places; in addition, there are neutral feeder cables starting from the substation and going to different points on the system with frequent grounds and taps to ramifications and to the neutral mains. The total amount of copper for neutral feeders is about one-twelfth of that for positive and negative feeders.

In a large system the amount of copper for feeders and mains in per cent of the total is as follows:

Feeders, positive and negative	58.9 per cent
Feeders, neutrals	4.8 " "
Mains, positive and negative	24.2 " "
Mains, neutrals	12.1 " "

Subway Ducts

Fig. 1 shows an arrangement of manhole, feeder junction box, trunk ducts and distributing ducts with a service handhole. Handholes are placed at convenient places along the distributing ducts and service connections are made to the adjoining buildings by tying service cables to the mains as indicated in the drawing.

These service cables are drawn in an iron or fiber pipe laid in the ground and ending in the basement or cellar of the building to be supplied.

Service Connections

At the customer's service the supplying company places a disconnecting switch and protective fuses and its current registering and metering devices.

Fig. 2 illustrates a type of modern service connection for lighting and power, consisting of specially designed porcelain blocks, which are equipped not only with fuses and all the connections to the watt-hour meters, but also with clips, by means of which the testing of the watt-hour meters on the customer's premises can be readily accomplished by inserting a plug with connections to the testing apparatus, thereby avoiding inter-

ference with the supply of current to the customer while the test is being made.

All of these appliances are enclosed under covers which are locked and sealed. From this point the customer derives his supply, three-wire for lighting and two-wire for power, which services are usually metered independently.

Standard Voltages

The usual distributing voltages used in this country are, $2 \times 110 = 220$ to $2 \times 120 = 240$ volts, though in a very few instances $2 \times 220 = 440$ to $2 \times 240 = 480$ volts are used.

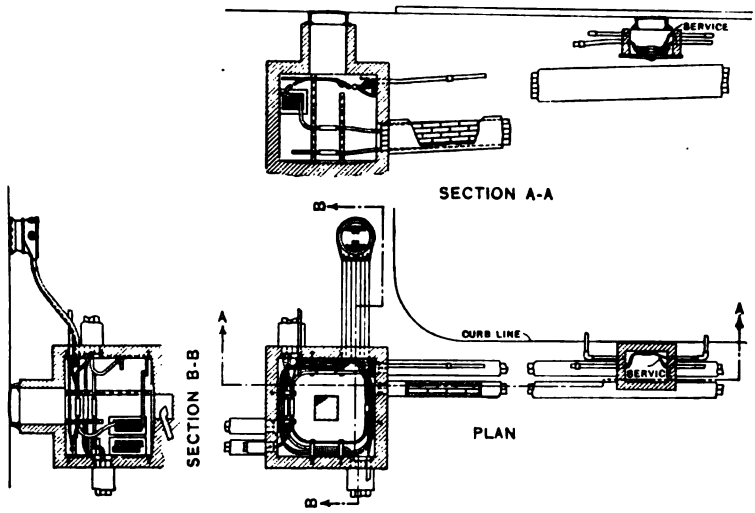

Fig. 1

If the multiple tungsten lamp eventually encroaches into the field of the arc lamp, the advantages of first cost and greater radius of the higher voltage systems would assume greater prominence than heretofore.

Substations

In general the full double voltage is generated by the converters or the motor-generator sets at the substation and the neutral of the system is secured by several means, among which are storage batteries, balancer sets, derived neutral from transformers, and other means.

Fig. 3 gives a diagram of the principal elements of a substation. The leads of the positive and negative connections are brought to separate boards. The neutral connections are made not at the board, but in the basement of the substation

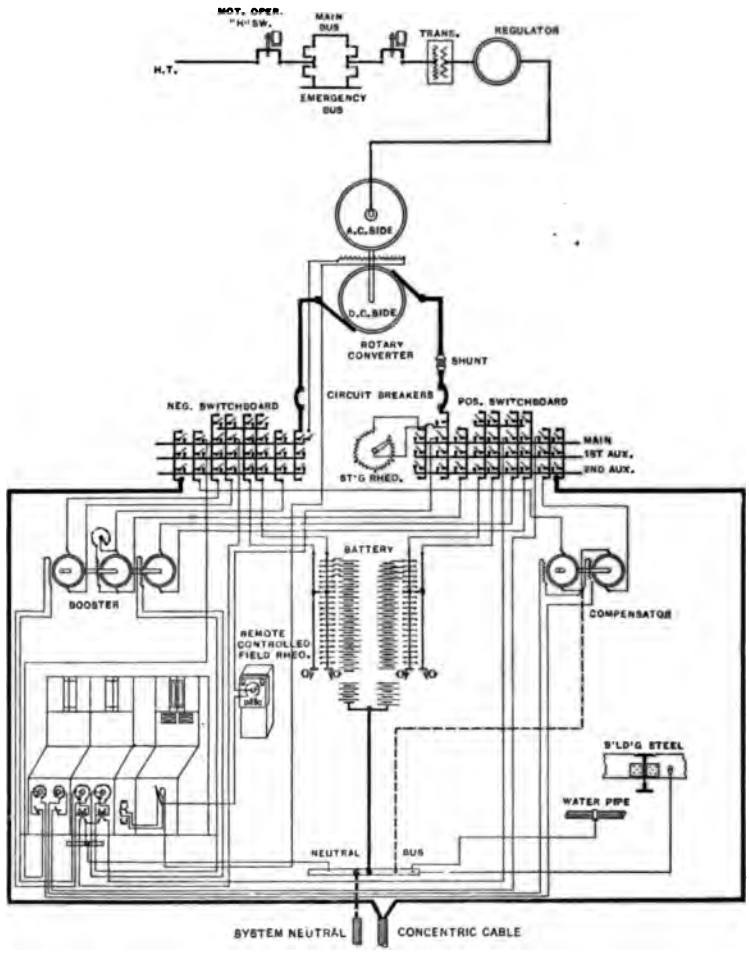

FIG. 3

or in the cable vault. Each of the two separate positive and negative d-c. boards is equipped with multiple buses, and all the feeder switches are selected to connect to any of these several buses. By this arrangement, according to the load requirements different machines can be operated on different buses at dif-

FIG. 4 [TORCHIO]

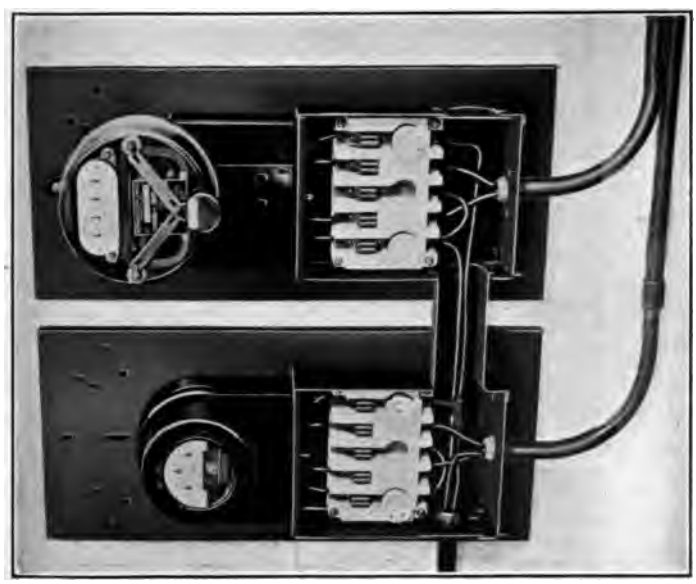

FIG. 2 [TORCHIO]

ferent voltages, and the shorter feeders can be connected to the low-voltage buses and the longer or more heavily loaded feeders to the higher voltage buses, thus securing voltage regulation throughout the network.

Fig. 4 illustrates the type of these selective switches used for converters and feeders, and the method of installation. By means of this edgewise system, the space occupied by the d-c. switches is reduced to a minimum, so that amounts of power as large as 30,000 kw. at 240 volts can be distributed from one substation.

The references give valuable material on the modern tendencies in substation design and equipment which cannot be treated fully in a brief review of this kind. We may mention, however, a few features of the latest developments which made possible large improvements in economy and simplicity of station. Among them stands foremost the development of the commutating-pole synchronous converter. This, in conjunction with graphite brushes with slotted commutators and self-lubricating copper graphite brushes for the collector rings, has made the operation of synchronous converters practically independent of attendance, except for the starting up and shutting down and the periodic cleaning and setting after the machines are shut down. Other important innovations have been the split-pole synchronous converter and the synchronous booster converter for obtaining regulation.

The manufacturers have produced units as large as 4000 kw. and they are now prepared to furnish still larger units if desired. Converters are usually six-phase and have been in many cases operated with double delta connection, though from recent tests it would appear that diametrically connected converters will operate practically under the same conditions as a double-delta-connected machine, and still have the advantage of greater simplicity of connections between transformers and converter. The synchronous converters are usually started from the d-c. end.

Air-blast transformers have been used most extensively and the practise of one large company is to have the blower motor connected directly to the secondaries of the transformers, so as to start it when the transformer is energized.

Storage Batteries

The installation of storage batteries at substations is a distinctive feature and great progress has been made in the last

few years in the adoption of the stand-by batteries, consisting of very thin plates, similar to those used for electric vehicles. These batteries can give for a short period of time large current discharges and often are designed to give, say for ten minutes, the full output of the substation in case of emergency.

Material improvements have been made in the method of end cell switch controls and connections.

Control

In very large systems great care is given to a number of such details, like the standard voltmeters for regulating purposes; the station lighting and power supply from duplicate sources; the telephone connections to the generating stations through independent lines and public telephone exchanges; and the emergency signals controlled from the generating station, giving simultaneous instructions by code to all the substations on the system.

APPENDIX II. ALTERNATING-CURRENT DISTRIBUTION

BY H. B. GEAR

The distribution of alternating current will be considered to include both *bulk supply* and *general distribution*. In the larger cities where the general distribution is made from substations, the bulk supply of energy is distributed by means of three-phase alternating current from the source of power to the points of distribution where it is converted to the form required for general purposes, for street lighting or for railway purposes. These lines are so numerous, and are so related to each other through tie lines, that they constitute a magnified form of distributing system with problems peculiar to themselves, which require consideration which might be lost sight of if they were classed as transmission lines.

Bulk distribution systems will be considered without regard to whether the energy is used for alternating-current distribution, direct-current distribution, or electric railway work, after its conversion.

Bulk Distribution

These systems are quite universally operated on the three-phase system at 25 or 60 cycles and at 6600 to 20,000 volts. The lower voltage is used where the radius does not exceed six miles (9.6 km.) and averages much less. In some systems the

longer lines have been raised to 20,000 volts or more, to handle the supply to suburban districts more flexibly. In the vicinity of Berlin there is an extensive 30,000-volt cable system serving the outlying parts of the city and suburbs. The German and English cable manufacturers have apparently been very successful in the production of cable for voltages above 20,000 volts, and such transmission lines are placed underground much more generally in Europe than in America.

The choice of frequency is fixed by the relative proportion of energy converted to direct current through synchronous converters. Where the direct-current load greatly predominates, 25 cycles is used and frequency changer sets furnish the alternating-current supply at 60 cycles. Where the alternating-current distribution predominates the power supply is often generated at 60 cycles. In several cases both 25 and 60-cycle generating systems are maintained, reserve capacity for each being secured through frequency changers.

Bulk supply systems have been developed in America chiefly on the principle of radial lines. A radial system is built up by the use of direct lines from power station to substation, one such line usually being sufficient to carry the load when the substation is established. The reserve source of supply, which is imperative, is usually secured by a tie line from another substation; or, in case of a small substation, by tapping another direct line at a convenient point. These conditions are illustrated in Fig. 5, which shows methods of supplying three substations of moderate size. In the three cases here shown it is assumed that the direct lines have a capacity of about 3000 kilowatts.

In cases *A* and *B* the failure of either direct line is provided for through the reserve tie lines. In case *B* a tap connection to one of the direct lines is used to save unwarranted cable investment. Either of the direct lines carries the entire load in conjunction with the tie lines in case of the failure of the other.

Case *C* shows the development of case *A* after the combined load of the three substations exceeds the capacity of a single line.

The ring system of case *A* may be used to take in any number of industrial power consumers up to the capacity of the cable; the substations in this case being on or very near the customer's premises.

The transmission system of one of the large companies in America has been developed on the principle of duplicate lines

arranged with substations in tandem. The converting units in each substation are divided into two sections so that an interruption on either line interferes with only one-half of the capacity in operation. These lines are protected by overload circuit breakers actuated by definite time-limit relays, so set that they will operate in tandem; that is, only that part of the service is interrupted which is beyond the fault in the cable.

As the loads increase and require more lines, the importance

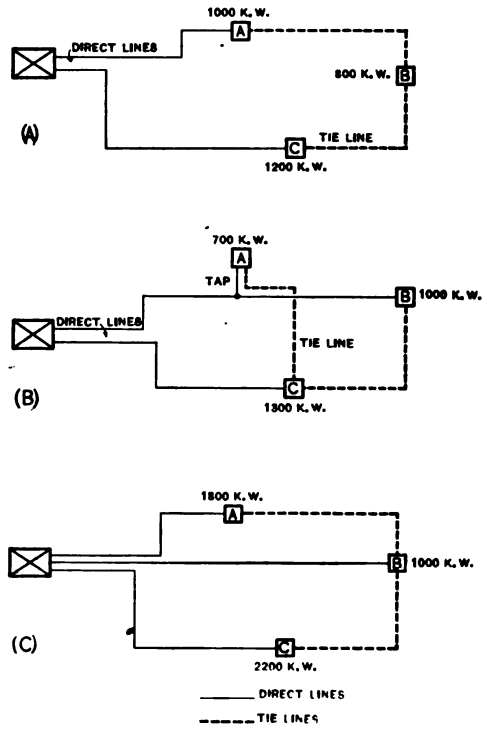

FIG. 5

of having a diversity of routes to guard against the failure of two or more cables to the same substation becomes apparent. This condition is illustrated in Fig. 6. The congestion near the power station must be guarded against by limiting the size of duct runs and providing several separate conduit routes.

As substation loads increase, the percentage of reserve investment becomes smaller, as one reserve line is sufficient for the three substations. Thus the reserve investment is about

one-eighth of the total in Fig. 6, whereas it is about forty per cent in Fig. 5.

It is usual to provide a transfer bus at substations so that any line can be connected to either tie line or to any converter.

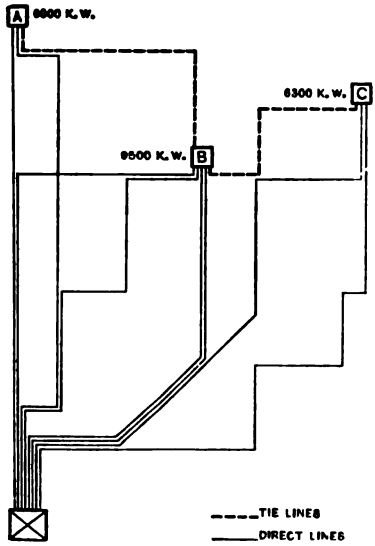

FIG. 6

A large proportion of the lines making up bulk supply systems in large cities is placed underground in lead-sheathed three-conductor cables drawn into ducts. The most economical use of capital is made when such cables are as large as can be properly handled. The kilowatt capacity of a high-tension cable at a given voltage increases more rapidly, with increasing sizes of copper, than the cost of the cable. The most economical cost per kilowatt, therefore, requires the use of as large a cable as it is practicable to draw into a standard duct.

The following table gives the maximum sizes of three-core cable which are installed at the present time and their approximate continuous capacity at various voltages:

Volts	Size of each core	Amperes	Kv-a.
6,600	350,000	290	3,200
9,000	350,000	290	4,500
13,200	250,000	220	5,000
20,000	150,000	145	5,000

The current values are taken for average conditions. They are somewhat high for situations where the facilities for heat radiation are poor, or where there is a considerable number of other cables liberating heat in the same duct line. These amounts of power could also be exceeded for a few hours during a peak load, without risk of injury.

Previous to the last two or three years it was not always

satisfactory to operate high-tension lines in parallel at the substation end, since a fault in either of the cables supplying a substation is likely to open the circuit breakers of cables not affected, thus shutting off the entire supply. This was due to the absence of reliable reverse-power relays which would permit the most satisfactory parallel operation.

Prior to the development of the commutating-pole converter, the largest unit which was considered advisable had a capacity of 2000 kw. These machines were designed to carry 2500 to 3000 kw., however, for about two hours. It therefore became common practise to have a line for each 2000-kw. converter or for two machines where 1000-kw. units were installed. Thus the average load per cable was about 2000 kw. under normal operating conditions, and as the cables used had a capacity of 3000 to 4500 kw., there has been an accumulation of surplus cable capacity amounting to from 50 to 80 per cent of the maximum substation load. This is particularly true of substations having loads above 4000 kw. The situation is such that there is, at the present time in Greater New York and Chicago, not far from $1,000,000 worth of surplus cable investment which could have been saved if means for parallel operation of cables and larger converting units had been available prior to 1910.

The introduction of converting units of 3000- to 4000-kw. capacity for direct-current work and three-phase transformers of almost any desired capacity for alternating-current distribution has done much to improve this condition in recent years. These units permit the use of cables at a point near their full safe carrying capacity and make possible large savings in future cable investment.

Another source of relief has appeared in the development of protective relays designed to permit lines to be operated in parallel. The Merz-Price system has had large and successful application in the north of England in a field where its value is greatest; that of the distribution of industrial power in blocks of 200 to 1000 kilowatts by means of a high-tension network. This system unfortunately involves the use of pilot wires which, not being included in existing cable systems, make its introduction more expensive and difficult than a system of reverse-power relays. (An interesting modification of the Merz-Price system, in which so-called "split conductors" render unnecessary the use of pilot wires, has been developed in England; but so recently that little definite experience is available.) How-

ever, it is probably the most reliable means at present known of guarding against interruption of service by cable faults.

Modified forms of reverse-power relays have been developed within the past two years, some of which are under trial at the present time. The performance and further development of these devices will be watched with the most sympathetic interest by all who are interested in getting high-tension cable investments down to a basis of economy comparable with other reductions made in plant costs in recent years.

Alternating-Current Substations

The alternating-current substation, in its simplest form, consists of a set of transformers with a minimum of switching equipment and auxiliaries mounted outdoors. After the load has grown so that two or more distributing feeders are necessary, circuit breakers, potential regulators and instruments must be added if first-class service is required. These require a building, the character of which is dependent upon the location and relative importance of the substation.

In substations of 1000 kw. or less it is usual to find oil-cooled single-phase transformers. With larger sizes, air- or water-cooled units are more economical. In three-phase systems three-phase units are often employed in sizes of about 750 kw. and upward. In two-phase systems which are operated in connection with three-phase transmission lines, single-phase transformers are selected for the Scott connection.

When the power supply is generated at 25 cycles the frequency-changing motor-generator becomes a factor. This usually involves synchronous motors and introduces exciters, starting compensator and necessary accessories in the way of switchboard equipment. Motors of frequency changers are usually wound for the transmission voltage to save transformer investment, where the transmission voltage is not above 15,000. Induction motors are used in some cases to secure greater stability at times of system disturbance.

The induction type regulator has largely superseded the transformer type. The superior results secured from automatically controlled regulators in the regulation of pressure have made them standard for important lighting service. The details of line drop compensators, contact-making voltmeters, and motor control have undergone a steady evolution in the right direction in recent years. The adjustment of springs and condition of

contacts, however, still require periodical inspection and checking of pressure at feeder ends. In Chicago it is found necessary with some 200 sets of equipment to check each of them at least once in three months by the installation of recording voltmeters for a few days at the feeder end.

The improvements in transformer design, by which weights and costs per kilowatt of capacity have been reduced, and the increasing requirements of good service, have made some striking changes in the cost of transformer substations. The transformers, which one ordinarily thinks of as the chief item, constitute less than one-third of the cost of a modern 5000-kw. substation, housed in a fireproof building and equipped with the required quota of oil switches, automatic regulators, duplicate buses, instrument and control panels, etc. The automatic regulators, feeder switches and distributing buses make up about half the total cost. A large part of the facilities of a modern substation is necessary for the safety of operating and construction men whose duties must be performed without accident to themselves, to the service or to the equipment.

General Distribution

The distribution of alternating current for general commercial purposes is accomplished in America almost universally by 2200-volt mains supplying step-down transformers located near groups of consumers whose premises are served by secondary mains at 110-220 volts. There are a few installations of low-tension alternating-current feeders on the Edison system at 110-220 volts in business districts, and some installations of 220-440-volt mains have been made where it was desired to avoid primary lines.

Lighting is quite generally served single-phase; while power service is given from two-phase or three-phase mains. Two-phase systems are in use chiefly where this method of distribution was established in the early period of development and is too extensive to warrant changing to the three-phase system. Three-phase systems are standard for all new installations where polyphase supply is desired for general power service.

Single-phase distribution is cheapest for lighting and small power mains at the load densities usually found outside of business districts, as the smallest size wire which should be used for mechanical strength is ample for ordinary loads. Three-phase, three-wire primary distribution is preferable in cities

where substation loads do not exceed 1000 to 2000 kw., but four-wire distribution is most economical for larger loads and the greater distances which usually go with them in the large cities. The four-wire system—being a 2300-4000-volt system—permits the supply of larger power users at outlying points more economically than by three-wire, 2300-volt systems.

The ability to regulate pressure independently on the different phases with greatly unbalanced loads makes possible the use of single-phase lighting distribution without sacrificing the advantage of three-phase transmission on the feeder.

The supply of power service in manufacturing districts is sometimes accomplished by the use of separate power feeders, the lighting being carried on other circuits. In other cases the light and power are combined. The use of separate power circuits tends to produce a duplicate distributing system and requires increased feeder capacity on account of the lower power factor, while with combined service the lighting tends to keep the power factor up. The diversity of demand between power and lighting loads also makes possible a considerable saving in feeder capacity where the lighting load in a given district is of the same order of magnitude as the power load.

Thus the policy of a combined feeder system is preferable from the standpoint of both feeder and main investment, in most cases.

With modern pressure regulating apparatus there are not many situations where the lighting service cannot be made what it should be, when power is served from the same primary mains.

The primary main system cannot be interconnected as the mains in a low-tension system, because it is impracticable to provide fuse protection in such a way that it will isolate a section of main which is in trouble without simultaneously blowing other fuses through which the energy is supplied. Thus the primary system loses the advantage of parallel feeding, and requires that the feeder end be located as nearly as possible at the electrical center of the district which it serves. The arrangement which gives the best distribution of pressure thus naturally takes the form of a center of distribution with radial mains. These centers of distribution should be chosen so that the drop on the primary main will average about 2 per cent from feeder end to transformers. This limit is not always commercially feasible in the case of lines to outlying districts where the load is not yet large enough to justify the cost of extending a feeder.

The usual form taken by single-phase circuits laid out in this manner is shown in Fig. 7.

In cases where a feeder follows a main thoroughfare along which most of the load is located, and the side branches are short, the tree system sometimes is used. This tends to give high pressure at the near end and low pressure at the far end but saves the cost of a "back feed" main.

In three-phase, four-wire systems a modified form of the

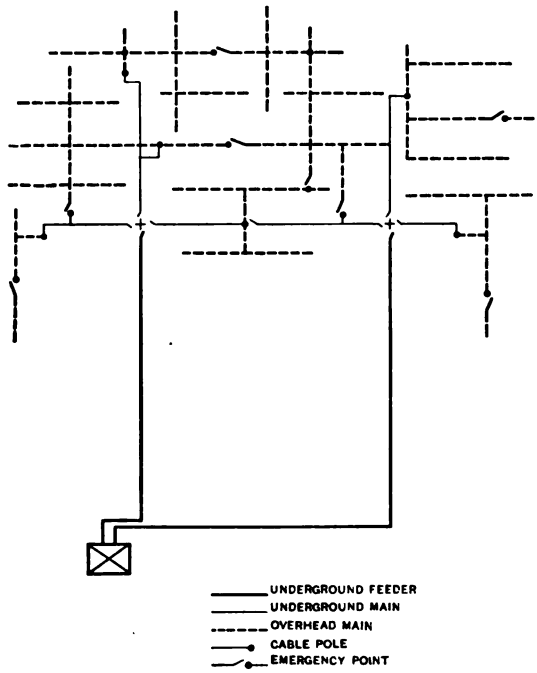

FIG. 7

center of distribution plan may be used, as shown in Fig. 8. The center of distribution of each phase is located with reference to the electrical center of the single-phase load carried by that phase. Since each phase can be regulated for pressure separately, this gives a good distribution in scattered districts, and permits feeders to be loaded more heavily than is possible when the load is distributed from a single center. In the denser business districts it is possible to pick up enough load for a feeder within a small radius, and a single center is adequate.

The separated centers of distribution can be used in two-phase systems but do not work out well for three-wire, three-phase circuits, since the line drop compensators cannot be set to take care of drop in the single-phase branch after it leaves the other phases.

Emergency Switching Points

Where portions of the primary system are underground and where mains of adjacent feeders come together it is important that suitable facilities be provided by which the mains of the two circuits may be joined together in emergencies. Cable

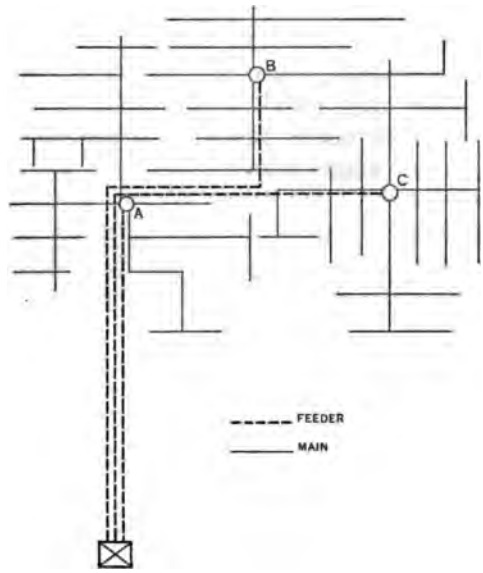

Fig. 8

repairs require a considerable time and if service is to be resumed promptly such emergency connections must be provided in sufficient number to permit the minimum interruption of service. Emergency switching points are also necessary as a means of putting sections of cable out of service while new cable taps are being cut in. The safety of linemen and continuity of service largely depend upon the facility with which sections of the primary main system may be controlled. Outdoor types of oil switches are used to some extent on important branches. The disconnecting type of porcelain pothead is found well adapted to this work, particularly at cable poles.

An arrangement of two adjacent feeders with mixed underground and overhead lines provided with facilities for emergency switching appears in Fig. 7. In case of the failure of any section of cable main, service may be resumed as soon as a repair man can open the potheads on the cable poles connected to that main, and close the emergency connection separating the overhead branches from the adjoining circuit.

Secondary Main Systems

The arrangement of secondary mains depends largely upon the density of the load. In outlying districts where the load runs from one to ten kilowatts in each block the size of secondary wires is comparatively small and the distances between transformers are such that the interconnection of adjacent secondary mains is not commonly considered desirable. The geographical arrangement of such mains tends to follow principal streets with few important mains intersecting. The failure of a transformer fuse under these conditions throws an overload on the adjacent transformers and the entire interconnected main is likely to be put out of service.

In the denser parts of a city where business buildings are served, a cross-connected network may be developed. This is less likely to cause trouble, as the load of any transformer in trouble is usually divided between more than two transformers, and the danger of blowing other transformer fuses is lessened.

The secondary system may be protected against trouble originating in the transformer by the use of "network protectors." In New York City it is customary to operate the larger transformer secondaries in parallel, using such a device quite generally. The "network protector" consists of a small transformer having the same ratio as the main transformer. The primary and secondary leads of the main transformer are carried through the protector in series. In case of a defect in the transformer the fuses of the protector quickly open the connections to the network and thus prevent the current from blowing the fuses of other transformers.

The interconnection of secondary mains has the advantage of permitting the use of spare capacity, where available, to take overloads on adjacent transformers. The diversity factor between different groups of customers may thus be utilized to make a reduction of transformer investment in some cases.

Motors cannot usually be served from lighting secondaries (except in the smaller sizes) without interfering with lighting service, on account of the fluctuations of pressure caused by starting currents. Where the requirements of lighting service are high it is therefore necessary to install separate transformers for power customers having motors of five h.p. and upward. In scattered residence districts it is often necessary to put motors of one h.p. and larger on separate transformers.

In alternating-current distribution in congested business districts where a network may be developed underground with loads of 75 kw. and upward in each block, it is very desirable to be able to serve light and power from one system except, perhaps, for users requiring about 20 h.p. and upward. The problem has been met in several instances by retaining the 500-volt direct-current distribution and establishing a three-wire Edison alternating-current network for the lighting and miscellaneous small power in the congested business portion of the city.

The secondary network of mains may be supported by transformers in vaults with primary feeders or by low-tension feeders from a centrally located substation. The primary feeder supply is the more usual as it follows the natural course of development.

As the load density increases the difficulties of getting ventilation and adequate space for the vaults multiply. The installation of a substation, centrally located, with alternating-current, low-tension feeders at the proper points, finally becomes the most economical and practical plan. About enough is saved in the cost of the vaults and transformers to offset the extra cost of feeders.

Where there is no direct-current power system provision must be made for alternating-current power service. In smaller cities this is provided for by separate transformers for the elevator service and for the larger general power. This permits the lighting to be served by single-phase, three-wire secondary mains.

In cities where lines are underground in the business district it is very desirable to be able to serve all customers from one set of mains as far as possible. This may be done by the use of four-wire, three-phase, 115-200-volt secondary mains supported by transformers and primary mains, or by low-tension feeders.

The proper distribution of lighting load between phases must

be maintained in order to avoid the effects of unbalance. The odd voltages of this system are a bar to its adoption if any considerable number of 220-volt motors is already in service, or if the lamps are rated lower than 110 to 112 volts.

When the load rises above 150 kw. per block, the problems of carrying large volumes of alternating current in lead-sheathed cables multiply, and a condition is reached where direct-current distribution seems to be a practical necessity from the cable standpoint, and the importance of the service requires the protection of the storage battery.

Transformer Selection

The determination of probable maximum demands of a user or group of users is of much importance in the selection of transformer sizes. Information based on experience and analysis of demands of different classes of users is necessary to avoid excessive investment in line transformers, as well as unnecessarily large core losses.

The systematic checking of transformer loads by the use of a suitable demand instrument is an important factor in keeping transformer investment within proper limits. This practise is followed by the larger central station companies quite generally. The practise of making contracts with large users on the basis of a demand measured by recording types of demand meters is of great assistance, as the maxima may be kept track of from month to month through the year and added load discovered as soon as it materially affects the demand.

The diversity factor in a group of consumers is so great in some cases that the demand of the group is very different from the demand of the individual users composing the group. The diversity factor is greater for residence consumers and similar classes whose use varies with their habits of living, than for commercial users whose requirements are fixed by more uniform conditions and whose demands individually are a larger proportion of their connected installation.

The following table represents average experience in the determination of demands of individual consumers and groups of consumers:

TABLE OF MAXIMUM DEMAND FACTORS

Classes of Users	Single	Group
Lighting Service		
Houses and Apartments	55 per cent.	20 per cent.
Offices	72 " "	60 " "
Small Stores	75 " "	60 " "
Hotels	35 " "	..
Churches	50 " "	..
Hospitals	60 " "	..
Manufacturing	70 " "	..
Power Service		
Less than 5 h.p.	86 " "	70 " "
6 to 10 h.p.	66 " "	62 " "
11 to 20 h.p.	65 " "	63 " "
Over 20 to 50 h.p.	53 " "	45 " "

The demand is given in this table as a percentage of the connected load.

Construction

The construction of alternating-current distributing lines for general service is very largely overhead. The use of underground work is necessarily limited to districts where the load density is such as to warrant the increased expense. In general, underground construction costs from three to five times as much as overhead work, where the load density is such as to require a 2200-volt main system.

Feeders and primary mains are sometimes placed underground on main thoroughfares, leaving the transformer secondaries and services overhead. This eliminates much of the risk incident to heavily loaded pole lines and avoids putting the more expensive part of the distribution underground.

The cost of distribution systems is materially increased by the necessity of doing the work piecemeal. The plant investment must be made with relation to the income which is likely to be derived within the period immediately following construction. The lines are therefore extended a block or two at a time, as the city grows, and the demand for service increases. The feeder system must be reinforced as may be necessary from time to time, to carry the added load. This involves re-arrangement of connections of primary mains and many complicated "cut-overs" which add to the expense very materially.

APPENDIX III. EFFECT OF CONSUMERS' APPARATUS AND WIRING ON DISTRIBUTION

BY H. GOODWIN

It is a comparatively simple matter to lay out a system of wiring a building, distribution lines and station apparatus which will give perfect service for any given combination of loads, but the duties of a distribution engineer are to make the best use of the lines available for supplying any proposed load without involving such cost as to make the proposition prohibitive from a commercial standpoint or without putting the consumer to such great expense for interior wiring as to make the service undesirable from his point of view.

When public electric service was first started it was for lighting purposes only. The service was generally only half night service; interruptions were frequent and voltage regulation was comparatively poor.

Conditions have changed and continuous good service has become in many cases a necessity.

Motor Service

The use of current for lighting was soon followed by the use of current for motors. These motors were at first small, and on account of the general irregularity of service no great trouble was caused by them. The power business has since become very important. The multitude of uses for small motors has also contributed very largely to obtaining many consumers for lighting. Since the introduction of electric current for power and lighting have gone hand in hand, it is natural that often a single service has been run for supplying both the light and the power and the consumers' wiring has been simplified as much as possible by the combination of lighting and power loads without regard to interference with service to one by the other.

Since motors cannot be started without a greater demand from the lines than is necessary to run them after starting, various well-known devices have been introduced to minimize the starting current.

Many electric power companies employ polyphase generation and both polyphase and single-phase distribution, the latter for lighting and small motors. In such cases it is necessary (in fairness to motor users as a whole and to the company) to have some fixed rule as to size of motor above which no single-phase service will be rendered and below which no polyphase

service will be rendered. This size varies from 1 h.p. to 7.5 h.p. with different companies, depending upon local conditions.

The polyphase motor means a lower initial and a lower maintenance cost for the user; and for the power company it means lower and better balanced starting currents and less interference with lighting service of other customers, but on the other hand polyphase motors mean greater line and transformer expense (except in large sizes) and greater metering expense. Such a rule as to maximum size of single-phase and minimum size of polyphase when once established in a community should be strictly adhered to, in order to save money both for the company and for the small polyphase motor user when he moves from one street to another.

In order to cut down the starting current the general practise is to require auto starters on single-phase motors from two h.p. up and on polyphase motors of five h.p. and up.

Many central stations are apparently satisfied to accept an installation with an automatic starter while others require that the starting device shall limit the current to a certain number of times the running current. Elevator and hoist motors are sometimes allowed a higher starting current than motors for general factory uses.

Recently automatic self-contained starting devices for motors have been marketed and have several obvious advantages and prevent unnecessary blowing of fuses.

The objections are that there is no adjustment by which the starting current can be reduced for classes of service where the starting torque may not be as heavy as the average and for which the motor must be designed in order that it may be adaptable to all purposes.

The general requirements for elevator motors are that they must be of the wound-rotor type. The device for cutting out the resistance is often mechanical and independent of the current drawn from the line instead of being directly dependent upon this current. It is very generally of a dash pot type which in use wears and works more and more easily, so that the motor is ultimately thrown across the line before it has reached speed at all.

In order properly to limit the starting current of an elevator motor cutting out the rotor resistance should be controlled by a device dependent upon the reduction of the current in the feed wires.

Summary of Motor Situation

In this motor situation it might appear that the manufacturer's point of view is diametrically opposed to that of the central station. The manufacturer can sell more motors if they can be made cheaper, but all the devices which the central station desires to protect its lines from occasional excessive currents cost much more. However, a broad view would indicate that the electrical art and industry will develop most rapidly and permanently by assisting in keeping as low as reasonably possible the rates for electricity, which cannot be done if central stations are put to excessive expense on account of the poor characteristics of the apparatus used by consumers.

Miscellaneous Apparatus

The question of allowing miscellaneous apparatus other than motors on lighting service still seems to be open and governed largely by local conditions. Rectifiers, cooking stoves, medical apparatus and the like are usually allowed on the lighting system, except where their use makes trouble. Wireless apparatus is generally classed as the most undesirable on account of the high frequency going back over the lines and burning out meters. It is generally required that this apparatus be supplied from a separate transformer.

Various electric welding and riveting machines are in use. Where the primary lines have a capacity of above 100 kw. these welders or riveters when used singly do not seem to cause much disturbance.

Consumers' Service Wiring

The effect of having to provide for the excessive current required for starting motors is that the consumer must wire, for all apparatus other than lighting and above ½ h.p., an independent service.

This service is connected to power mains which are standardized at 220 volts. This then makes it necessary to require that all motors of ½ h.p. and above be made 220-volt.

In places where practise has not advanced so far as to require a separate power main, it is also found well to require that all motors of ½ h.p. and over be made 220-volt, in order to minimize the starting current and its effect on the light.

Emergency Service

The necessity for emergency supply for industrial service is

a matter on which there is much diversity of opinion. In general, some emergency supply is justified when the load factor and demand are large enough to bring the investment and operating costs below the average. Unusual restrictions are placed upon services for fire pumps by the underwriters, based apparently upon an assumption that electric service is not dependable in an emergency. Continuity of service is now so well established that it would seem to be time for a readjustment of these rules.

Underground Service

The policy of introduction of underground service from underground lines by the central station company seems to be uniform. There is still, however, a divergence of opinion on the question of introduction of underground service from overhead lines. Some companies require lead-covered cable while others are satisfied with rubber-covered wire. However, the best practise would seem to be that the service be installed by the company. The expense must be borne by either party according to circumstances.

Relation of Consumers' Apparatus to Charges for Service

It is proposed to consider the effect of consumers' apparatus on the charges for service. Rates are often based upon a charge for kilowatt-hours with a minimum charge and discounts for greater use. This minimum is usually based on the rated horse power connected to the service or on demand measurement.

The use of the Wright demand meter makes it an advantage to the consumer to have apparatus of high power factor, since the meter registers maximum amperes.

There is on the market a motor which gives unity power factor and thereby improves the general power factor of the system. Where such a motor is available arrangements could be made which would either reward the consumer for buying apparatus of good power factor or penalize him for buying apparatus of poor power factor.

It would seem to be well if some system could be worked out for basing the minimum charge on the starting current of a motor instead of on the horse power rating.

If a system of charges could be instituted which would penalize the motor with heavy starting current or exempt in some degree the motor with small starting current it would appear to be a great advantage to both the central station and the customer.

Summary

Generating and substation service has now reached a very high plane of excellence. Small details of distribution tend to interfere with the regulation and service at the critical point where it is supplied to the consumer.

The solution is the placing of proper limitations on, and requiring the proper arrangement of, consumers' apparatus and wiring. There is a wide diversity of rules on this subject at the present time, but even the best leave something to be desired.

Therefore, let us look for improvement in these rules so that they may call for what is vital in this matter, which affects not only the procuring of new customers but the giving of good service to all.

APPENDIX IV. DIRECT-CURRENT DISTRIBUTION FOR SURFACE RAILWAYS—URBAN SERVICE

BY R. H. RICE

Electric railways very frequently have energy furnished to them over high-tension alternating-current transmission lines, and in this section of the report the substations are included in the distribution system. The component parts of the distribution system for urban street railway service are then:

1. The converting equipment in the substation;
2. The positive system from the substation switchboard to the car, including feeders and trolley wires;
3. The negative system, or returns, which complete the electric circuit from the car to the substation negative bus and include the electrical features of the track.

The usual city street railway system is characterized by having rather short feeding distances, large and rapidly fluctuating loads, and a wide variation in energy requirements at different hours of the day. Public demand is increasingly insistent upon quick and adequate service, better light and more heat, and this requires a greater amount of energy to be cared for in the distribution system, and greater reliability in its operation.

Substation Equipment

Substation equipment has become quite standardized and various installations differ chiefly in arrangement and in minor details. The equipment in a modern substation is housed in a well-lighted and ventilated building constructed for this purpose. It should be so arranged as to leave ample space for making repairs, and for installing or removing parts as may be necessary. A traveling crane is usually provided to facilitate such changes, but is now frequently omitted as the standard modern machinery is so reliable that it is rarely necessary to make replacements of parts requiring the use of a crane. Not only is there a saving in the investment for a crane but the building may be made lower and the side walls somewhat lighter, thus making an additional saving. Frequently no heating plant is installed, as the waste heat energy from the machines is sufficient to give a comfortable working temperature.

The supply of energy to a substation is almost universally from three-phase high-tension lines, and for railways is of 25 cycles. For city service such high-tension lines should be, and usually are, underground, to ensure more reliable service and to prevent danger to the public from exposure to high voltage. Conversion to direct current in the substations is by the universally accepted machine, the synchronous converter. It is desirable to have a separate high-tension line to serve each converter when the machines are of large capacity, and used in important city service. Switching arrangements are made to use any converter with any incoming line, so while the normal operation on the alternating-current side is by independent units of high-tension line, transformers, converters and other apparatus, emergency connections may be made as desired to interconnect the units. On the direct-current side the converters are operated in parallel, being connected to common positive and negative buses.

The synchronous converters used for railway purposes are 600-volt direct-current, compound-wound, and the later machines have commutating poles. Just a few years ago a 2000-kw. unit was the limit in size, but 4000-kw. machines are now in service. The cost of these large machines is less per kilowatt and they occupy but little more space in the substation, making the area per kilowatt much less than formerly. It is possible to place a 4000-kw. machine on the same foundations formerly occupied by a 2000-kw. unit. Care in design has

made this improvement possible, and the later machines contain numerous refinements in design which in the aggregate improve this class of machine very materially.

Switching is performed by motor- or solenoid-operated oil switches controlled from the main switchboard, and energized from a low-potential storage battery circuit. This battery circuit also provides current for the switchboard and station emergency lights.

An effort is made to keep the power factor of each station unit as near 100 per cent as possible. The rotary shunt field and the reactance are so adjusted that with a given high-tension line voltage and direct-current voltage the converters will operate with 100 per cent power factor when fully loaded. If the converters are operated under overload conditions there will then be a leading power factor, and if operated under less than full load there will be a lagging power factor. Most railway substations can operate very near to 100 per cent, and this is usually desirable when energy is purchased from a central station company. In some cases a penalty is attached, in the way of increased power cost, when the power factor deviates from 100 per cent.*

The Positive Feeder System

There is not much variation in practise among companies in positive feeder distribution. In general the trolley line is sectionalized by line breakers or section insulators, placed as desired, and each section is fed from a separate feeder panel in the substation. This feeder is very often composed of several cables running by different routes and tapping in at different points to a distributing cable running along the street, from which feed taps are made to the trolley wire. The above "radial" system of distribution is not so economical of copper as a "network" system in which all of the trolley wires form a continuous network and the feeders furnish energy to selected points of the network. As the load shifts from point to point all of the trolley wires and distributing cables act as equalizers and feed current to the point needed. It is difficult to locate trouble in an extensive network of this kind and also difficult to isolate the portion in which the trouble occurs, so that this method is not in common use. Some effort has been made to

*See "Power Factor Control by Rotary Converters," Nicholas Stahl, *Electric Journal*, December, 1913.

utilize the advantages of a network with the radial system by joining adjacent trolley sections through fuses or circuit breakers. Such a method has not been found satisfactory because it was impossible to adjust the connection so that it would distinguish between a heavy transfer of current from one section to another due to shift of load, which it should allow, and a heavy flow of current into a section due to short circuit, which it was not intended to permit. As a result these section connections usually became so unreliable that they could not be depended upon and were abandoned. A common practise at present is to provide knife switches, mounted in a pole box, which are normally open, but which may be closed on each end of a section if for any reason the feeders to this section become disabled. Such a plan provides a quickly operative and convenient device for ensuring continuity of service, as it is quite unlikely that the two sections adjacent to a disabled section would also be out of service.

The feeders may be underground or overhead. In the largest cities, and in many of the smaller ones, the municipalities require underground distribution at least in the central business district. The underground cables are installed in tile ducts and at frequent intervals lateral connections are made between these cables and the trolley wire overhead. A typical lateral connection consists of a tile duct, or fibre-lined iron pipe, running from a manhole to an adjacent trolley pole, and connecting with a vertical fibre-lined pipe clamped to the pole. This vertical pipe should be at least 10 ft. (3.04 m.) high, and just above its upper end a switch box and lightning arrester are attached to the pole by means of brackets. The lateral underground cable is run from the manhole to and up the pole and connected to the switch. Between the top of the pipe and the switch the cable should be stripped of its lead sheath, taped and painted with an insulating paint, and the top of the pipe should be capped with a split wood plug which is cored to fit the size of the cable used in the lateral. This should be done to keep snow and rain out of the pipe.

The lightning arrester is attached to the riser from the switchbox and the ground wire passes down through the pipe to a ground rod in the floor of the manhole, or is attached to the rail. The mode of grounding the lightning arrester is a disputed point to some extent, but undoubtedly a good connection to moist earth is preferable to grounding to the rail. Running

the ground wire through the lateral pipe may also cause some trouble, but this is frequently done, as no better method is usually available.

These laterals, although a relatively small part of the distribution system, may, if they are improperly insulated or installed, become the weak links which determine the strength of the whole distribution system. All cables should be rubber-insulated, the clamps holding the weatherproof riser to the pole should have an insulating band between them and the pole, and the cable should be held in the clamp by a split insulator. This gives three insulations between the conductor and the pole and will practically prevent "hot poles."

When the feeders are overhead the connection to the feed span is very simple, using either a jumper or making the span up with a tail. In this case lightning arresters are spaced along the line as local conditions demand, probably about five or six to the mile on an average.

The most commonly used trolley line construction is the standard span supported on tubular two- or three-section steel poles set at the curb line. The span wire almost universally used has been galvanized steel, but silicon bronze strand or copper-covered steel wire is now meeting with considerable favor. It has been found that steel strand frequently has very short life, especially in some manufacturing localities where atmospheric corrosion is especially pronounced, and other material resists such corrosion better than steel strand. The span should have two insulators cut into it between the trolley wire and the pole, and these, with some form of insulating hanger for the trolley wire, give three insulations from wire to ground. Clinch ears are to be preferred to soldered ears and are more frequently used. The tendency is toward simplicity in construction, but with such means as will increase safety and reliability.

Overhead trolley special work is an important item in construction. There are many complicated layouts at busy corners, and reliability of construction is paramount. Often with long cars it is necessary to set poles considerably back of the curb line to secure proper clearance on curves, and sometimes the city authorities require that poles be set back to the building line at important corners. It is desirable to develop standard layouts which are designed with a minimum amount of overhead material, and in which the stresses are so balanced as to secure reasonable assurance of permanence in the structure. In such

construction great care must be taken to align the trolley wire so that the trolley wheel can readily follow it without undue restraint.

In the 1913 report of the Power Distribution Committee of the American Electric Railway Engineering Association may be found specifications for material and construction of overhead trolley lines. In the various annual reports of the Board of Supervising Engineers of Chicago will be found the results of numerous tests on trolley material, such as poles and strain insulators, and also descriptions of special forms of construction. One of the most difficult things to secure is a good quality of trolley wire. High conductivity has been assumed as the chief criterion in securing a first quality wire and other desirable qualities have been sacrificed to secure this one. For a city system, with dense traffic, many feeders and frequent taps, the conductivity of the trolley wire is not of paramount importance. The qualities of toughness and high tensile strength are most important and it is desirable to place an upper limit on the conductivity and make the other requirements more severe than has usually been the case. The particular qualities required and the method of securing them in trolley wire is a subject worthy of considerable further study.

In any street railway system the load will fluctuate widely and it is a question of importance to determine upon what particular basis to design the feeder system. The load factor, that is, the ratio of the average load during the day to the maximum within the period, is usually from 40 to 50 per cent in an ordinary railway system. If the feeder system is designed to carry the peak loads without an overload on the cables, then during a large part of the day the current in the cables will be far below their safe carrying capacity and considerable copper will be idle. On the other hand, if the feeder system should be designed on a basis of say a six-hour average load, then the cables would be subjected to large overloads for a considerable period of time, heating would occur, the cables would more rapidly deteriorate, and a shorter life would result. The two-hour average is a good basis for feeder calculation, as the ordinary percentage of load in excess of this value is well within the overload capacity of the cable, especially since this excess load lasts for such a brief time. If this basis is assumed it means that the feeders will carry the entire load without being overloaded, except during two-hour morning and evening peaks.

The detailed method for computing the feeders necessary for a city system has been fully described by the writer in a paper published in the *Journal of the Western Society of Engineers* of June 1910, and in the Second Annual Report of the Board of Supervising Engineers, Chicago. Briefly, the method is to determine from the proposed operating schedules the total number of cars required during the "rush hours," and plot them upon a skeleton map of the system, thus making a "spot map." The afternoon maximum period is usually the heaviest service period, so that the car distribution for two hours of what is styled the "p. m. rush" is used on the map. On another map the trolley sections are indicated and the number of cars in each section determined from the spot map. This number of cars is then multiplied by the previously determined amperes per car, giving the current load for each section, which is placed at the center of load of that section. The required number of amperes per car should be determined in all cases by tests upon the particular equipment used and service demanded. This map is the "load distribution map" and shows very clearly the energy requirements of the system.

A study should then be made of the proper location of substations. The best probable locations and trolley sections for each station are selected and a graphical calculation of load center for each station is made by finding the combined center of gravity of the loads about each station. If the station locations chosen are not the most economical for distribution of copper, studies are made of comparative costs for other locations where the company may have property or where real estate may be obtained to advantage. After the station locations are definitely settled and shown upon this "station load center diagram" and the sections to be fed from each station are decided upon, light radial lines are drawn on the "load distribution map" from each station to the center of load of each section, which shows at a glance just what streets are fed from any given substation. Because of its appearance this modified "load distribution map" is known as the "spider diagram."

The most desirable routes for the cables are then determined, and the distance from the substation to the center of load of each section is measured on a large-scale map. After the computation of the cable necessary for each trolley section has been made a "feeder diagram" is prepared. This shows, by a properly selected code, from which substation each trolley section

is fed, the number, size and route of all cables, and whether the cable is underground or overhead.

The calculation of the size of feeders to serve any given trolley section depends upon four elements:

1. The load in amperes upon the section.
2. The distance of the section from the station.
3. The allowable drop in the feeders.
4. The current-carrying capacity of the cables.

It is desirable to limit the cables used to a few sizes only which may be kept in stock. The labor cost of replacing cables is practically independent of the size, and the larger sizes are thus more economical than the smaller. For underground cables the 1,000,000-circular mil size is a desirable maximum as it is readily installed in a standard 3 or 3½-in. (7.6 or 8.9-cm.) duct, in lengths convenient for handling. The current-carrying capacity of a cable does not increase as rapidly as its cross-section, because of the inability of the cable to radiate the heat developed. A great deal of study has been made upon the carrying capacity of cables, but no very definite knowledge has been obtained, or at least made public, upon the safe capacity of cables of various sizes and kinds in ducts constructed in ordinary street soil. A carefully conducted series of tests, having this end in view, would be very desirable. In overhead lines the maximum size of cables is determined almost entirely by the weight of cable it is convenient to pull over the cross-arms and to handle upon the poles. Probably the most common size in city service is 500,000 circular mils.

The allowable drop in a feeder may be of any value desired and it is not usually fixed at the most economical value. For a city system subjected to large peak loads a small drop, even at peak loads, is desirable even though it is not economical with respect to feeder investment, because it is important to operate the car motors at approximately their rated voltage, and the public requires good illumination in the cars, which cannot be secured with a fluctuating voltage. A value of 10 per cent positive line drop under peak load conditions is not too good a standard to set, as this means a 60-volt drop on the common 600-volt system. Even this is too large a drop to allow unless the negative return circuit is also designed for a small drop.

The load on the trolley section, and the route of the cables, have been determined as previously explained. It is only necessary to measure the feeding distance on a large-scale map and

then the elements of the computation are all known. The first step is to select the size of cable necessary to carry the load, and then compute the drop. In general for those sections near the substation the cable size fixed by current-carrying capacity is the proper size to use, but for the more distant sections the voltage drop limitation may require an increase in cable size. To make such calculations readily a chart may be used in which are curved lines of constant product, and superimposed upon these are radial lines showing the relation between distance and drop for various sizes of cables. Numerous other means have been devised for making the same calculations, but unless there is a great deal of computation to be done at one time special methods are not needed.

When a number of stations furnish energy to a city system, each station has a feeding district of its own and may operate independently of every other. But it is usually advisable to operate such stations in parallel so as to distribute the load and to have the benefit of assistance from other stations adjacent if any one is partially or wholly disabled.

Theoretically, the best manner of accomplishing this is to provide direct equalizing ties between the positive buses of the stations just as machines are equalized in a station. The objection to this is the large cost of the cable which is necessary, and which is not utilized directly in furnishing current to the cars. Essentially the same result may be accomplished by feeding a number of the more important trolley sections from two separate substations in such a way that in case of the shut-down of one station or of accident to one feeder, the cars on these sections could still be operated from the second station. These are designated as "tie-sections," and in addition to the above advantages, the feeders are so proportioned and calculated that on the whole system, in case of the shut-down of one or two stations, the cars on the more important sections can be operated from the remaining stations by interconnecting through these tie sections. The amount of energy drawn over these tie lines is regulated both by the relative resistance of the cables and by voltage control in the stations. This tie line system represents in a measure the factor of safety necessary for successful operation. The number of such lines varies with the importance of the stations and the density of traffic on the individual sections fed from them.

The Return System

The design of any overhead trolley system naturally involves provision for as direct a return of current as possible to the negative station busbar. Practically all city railway systems use grounded return circuits, the negative side of the distribution system being connected to ground. Although utilizing the full carrying capacity of the track rails insures that the greater part of the return current will follow this path, a certain proportion may reach other metallic underground structures which happen to offer another return path to the locality of the substations. It is very desirable to limit these "stray currents" to a small value in order to reduce the possibility of electrolytic damage to a minimum. Another decided advantage in making the return circuit very good is of course to reduce the energy losses. It is too often the case that the return circuits, except possibly for rail bonding, are almost wholly neglected, while the positive system is carefully planned and constructed. A poorly built negative system does not jeopardize life or cause delays to the same extent as similar neglect in the positive system would do, but elements of danger and loss are present which should under no circumstances be neglected. Negative feeders are unlike positives in that the cables form a network all connected to the tracks, instead of a group of independent cables running to unconnected portions of the trolley wires. The earliest form of return circuit was the rails only, which were bonded at the joints, and later a connection was made at the power station between the rails and the negative bus. As the loads and distances increased the drop became excessive on these simple track circuits, and supplementary conductors were provided to reduce the drops. The simplest method of doing this is to provide return conductors in parallel with the rails, and in such sizes as to reduce the return drop to the required amount. As approach is made to the substation the current increases, due to the accumulated load, and in order to keep the return circuit from being overloaded the supplementary conductors must be increased more and more the nearer the approach to the power station. The amount of such supplementary copper necessary is computed from the allowable maximum return drop.

It is difficult to make a calculation for this supplementary copper in the case of a city system whose tracks form a complicated network of conductors. But it can be done by assum-

ing the load distribution as in the positive feeder calculations and applying Kirchoff's laws to each element of the network formed by the intersecting tracks. The track lengths, conductivity, and loading being known, the drops may be found. If the drops must be reduced, this may be done by reinforcing the track circuits by additional copper.

In a grounded system, using the rails and supplementary copper for returns, in order to secure the full benefit of the supplementary copper it is necessary to connect the tracks frequently to this copper. This bond serves as an equalizer between tracks and enables the full track and cable conductivity to be utilized when the load is all on one track as well as when evenly distributed. The supplementary copper should be run through all special work and directly to the negative busbar. Where two cables cross, as at intersections, they should be electrically connected so that their equalizing effect may be realized. All rails on straight track should be at least well bonded, and preferably welded, so as to make the joint as good a conductor as the stock rail. At track special work, such as intersections, curves or crossovers, it is not usually feasible to weld at the rail joints, and the special work may thus be cut off from good electrical connection with the tangent track. To preserve the conductivity of the track circuit, special work cables are run through the special work and welded to the tangent track at each end. The value of the return circuit thus does not depend upon the special work rails, which may be removed without materially affecting the conductivity. Further details of such a system, and the results of tests on cable and bond terminals used as outlined above, may be found in the Third Annual Report of the Board of Supervising Engineers, Chicago, 1909.

The "insulated return system" is another method of constructing a railway return circuit. In this the return current is taken from the track circuit at various points, selected so as to maintain the track drop within any desired limits. The drop on the insulated cables may be of any amount up to the value which will cause the current to equal the carrying capacity of the cable, and the drop may or may not be of the same value on all the cables. The tendency will be for the shorter cables near the substation to become overloaded and sometimes a resistance must be inserted in these cables to limit the current and make the drop approximately equal to that on the other cables. It is possible to use negative boosters with these

insulated returns, but they add much to the operating difficulties, and have found no favor in this country. The insulated return system has been used much more extensively in European countries than here. Two papers* bearing especially upon this subject have been presented by Messrs. J. G. and R. G. Cunliffe and appear in the *Journal* of the Institution of Electrical Engineers.

Numerous matters of interest have not been touched upon in this report, but an attempt has been made to cover the fundamentals and to record good modern practise. Some important matters of design, such as the most economical number of substations, their location, and the maximum economical feeding distance, have not been discussed. Other matters of less theoretical character offer equal opportunities for investigation—such as the possibility of using higher voltage in operation, and the use of some form of three-wire system.

APPENDIX V. DIRECT-CURRENT DISTRIBUTION FOR UNDERGROUND AND ELEVATED RAILWAYS

BY E. J. BLAIR

The term "underground and elevated railways" used in the title of this report refers only to such railways when used for passenger service in large urban centers. The word subways may be substituted for "underground railways" to make the meaning more clear.

The railways of this description at present in operation or under construction in the United States distribute direct-current energy at approximately 600 volts bus pressure, using in general a third rail for the working positive conductor and the track rails reinforced by other conductors for the return circuit. Therefore this type will be given specific attention, although before passing to the details, mention will be made of other methods of distribution.

With the same type of distribution there is of course the possibility of increasing the potential. This would not seem desirable, thereby causing a departure from the established equipment standards, because for subways and elevated roads the density of loading will always be rather heavy on account of the class of service. This necessitates numerous distributing points, and on the other hand the length of feeding will

* "Electric Traction Vagabond Currents," Vol. 43, Part 197 (1909), and "Tramway Feeding Networks," Vol. 50, Part 219 (1913).

never be very long, so that 600 volts bus pressure can be accepted as good practise and the advantage of higher pressure would not offset the disadvantages. For the same reasons, no time will be spent in discussing the matter of alternating current.

Passing to other types of direct-current distribution, several modifications of a three-wire system are used in different parts of Europe. The most radical of these is the method used in the subway of the City and South London Railroad, which is a double-track tube using the third-rail conductors of the two tracks as the outside wires of the circuit and the running rail as the middle or neutral wire. This of course has the effect of minimizing the current flow in the track rail and thereby eliminating trouble from stray currents. However, such a method is only possible with a small and simple system, wherein the current loads are practically balanced between the two tracks. Another similar method is that used in the Nord-Sud subway in Paris, where a third rail is used for one side of the circuit and an overhead trolley wire for the other side with 1200 volts between the two and 600 volts from either to the track rail. This method would seem to be preferable to that of the City and South London, since it is not necessary to balance one track against the other. It also is used for the purpose of eliminating stray currents from the grounded track rail, by reducing the current in the track rail.

In London in most of the subways and tubes a fourth rail is used for the negative conductor, placed on the opposite side of the track from the third rail or more generally in the center of the track. This scheme of course entirely eliminates the difficulties from stray currents from a grounded track rail, since both sides of the circuit are insulated. It introduces operating difficulties due to the addition of the fourth rail, especially when one side of the circuit becomes grounded, as sometimes the results react upon equipment at distant parts of the line. It also adds to the burdens of maintenance, and complicates construction, especially at cross-overs and switches. Such a system is quite necessary in London on account of the severe limitations of return circuit drop imposed by the British Board of Trade when grounded conductors are used. With ordinary care the drop in track rail return circuits in the class of service under discussion may be kept within such bounds as will not cause electrolytic damage, and therefore to resort to

the fourth rail would not seem necessary unless municipal regulations exact it or unless for any given condition good engineering economy justifies it. However, in laying out a new system it would always be well to weigh carefully the merits and costs of the fourth rail system against the method of track rail return with its necessary auxiliary copper.

The type of construction common in the United States, namely the third rail with track rail return, is the particular object of study of this paper, since it is most common and more nearly meets all conditions. Where traffic is so dense as to require the construction of an expensive subway or elevated railroad, then the distribution must be laid out in such a way as to fulfill the following conditions, namely:

a. The maximum of reliability.

b. Ability to care for peak loads out of all proportion to mean requirements.

c. Heavy currents per train unit, and such close headway that extreme current densities obtain per mile of track.

In laying out such a system, therefore, the problems of size and amount of conductors, etc., are the least difficult for the engineer to solve, and the most important feature to be considered is that of simplicity and perfection of operation. The tendency has been to lay too much stress on the former and not enough on the latter. The methods of computation for feeder sizes, etc., described in that portion of the report given over to surface car systems, may be applied to some extent to calculations for elevated and subway work. In considering the operating features we find that the arrangement and division of the electrical distribution with respect to the track, or what is called sectionalizing, is worthy of the most careful attention.

An elevated or underground railway is, generally speaking, not composed of the complicated network of tracks and line distribution that is found on a surface car system in a large city. In other words, the current is distributed from substations or power stations in a straight line on both sides of the station, whereas for surface car systems the distribution radiates in all directions from substations. The fact that we have no networks to consider makes positive and negative distribution a much more simple task from the purely electrical engineering viewpoint, than is the case on surface roads. There seems to have been a tendency, however, to follow their precedents originally in methods of sectionalization, especially as to the

matter of connecting both tracks of a double-track road to the same electrical section. This scheme may have its advantages in economy of distribution, but its great disadvantages from an operating point of view more than outweigh such advantage. In effect it makes a single-track railway out of what should be a double-track road.

Investigation has been made of several properties, each having different methods of sectionalization and all of them fairly typical of conditions throughout the country. One of the methods is that described above, namely, both tracks being tied together. In another case a large part of the railroad is

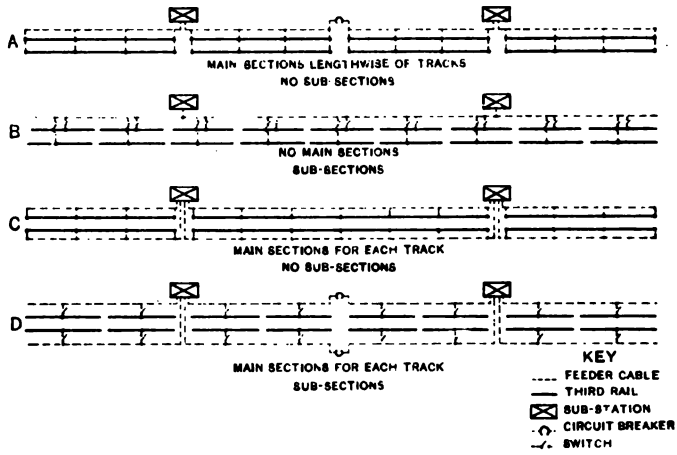

FIG. 9

connected on one common system of feeders, and switches every few thousand feet along the track are employed for isolating parts that are in trouble. This system is even more difficult to operate than the other. Still another system, and the best of the three, separates the two tracks from each other and also breaks the system up longitudinally at intervals. This latter system employs practically no track switches and therefore puts all section circuit breakers and switches on the switchboard in the power house or substation.

The diagrams shown in Fig. 9 typify these three systems of sectionalizing, with a fourth that is more nearly the ideal one. In each diagram a double-track road with no branches and with two substations is used to illustrate.

Fig. 9A is the system with the two tracks connected together on the same feeder cables and hence on the same circuit breaker or breakers in the substation. It is divided lengthwise at points opposite the substations and at a point half way between the two. At this latter location switches or circuit breakers are installed. Thus there are four sections shown. Of course in many instances there may be additional sections on the ends, with independent feeders. This system uses the conductivity to good advantage, but it is at once apparent that a short circuit of either momentary or prolonged duration on either track affects the other track and causes operation in both directions to cease.

Fig. 9B shows both substations feeding in on a common bus, that is, all feeder cables and conductor rails are connected in one general section. This also is very economical of copper, but usually necessitates several circuit breakers being in parallel on the distributing board, a condition which in itself is undesirable. To give an opportunity to isolate trouble, either track switches or track circuit breakers are installed at intervals of a few thousand feet. The track circuit breakers, to be effective quickly, both on opening and closing, should be controlled from the substation. In either event, whether they are remote-control or simple circuit breakers, a large amount of maintenance is entailed on account of the number involved, and the fact that they are not under the eye of an attendant. It has been found desirable on one road to eliminate the automatic circuit breakers and rely on switches only. Even with the circuit breakers, a heavy short circuit is apt to open the entire section at the substation. With such circuit breakers of the ordinary simple type it is also quite likely that one may open and leave its particular sub-section dead until such time as some one closes it, which usually involves a little delay. All things considered, it is felt that such a layout is even less desirable than that shown in Fig. 9A, since there is no sectionalization directly under the control of a skilled attendant, unless the remote control feature with its complications is resorted to.

In Fig. 9c the tracks are separated from one another and each track is sectionalized longitudinally, opposite the substation. Additional division may be had at as many points as may be desired along the track, necessitating additional feeder cables and panels. However, the substations will usually be sufficiently near together to do away with the necessity for this ad-

ditional division. It will be noted that the sections between the two substations are common to both or are "tie sections." This may be done either solidly or through switches or circuit breakers. This method is not as economical of copper as that of Fig. 9A or 9B, but is very satisfactory from an operating point of view. The only bad feature is the two substations feeding into the common sections, making it necessary to get both ends open in case of trouble. It has sometimes been found advisable, in order to secure better economy of distribution, to connect the two tracks together through equalizing circuit breakers. This, however, adds another complication when quick opening is desired. In general a system of this sort operates very satisfactorily.

Fig. 9D differs very little from the scheme shown in Fig. 9c and is the ideal to be worked toward. The "tie sections" are connected through circuit breakers, preferably remotely controlled by one of the substation operators, or, if at a location convenient to interlocking tower or dispatcher's office, by the attendant at such places. Sometimes the use of a circuit breaker with a no-voltage release is all that is necessary. It may seem that "tie sections" are not necessary, but in actual practise they are very desirable, since they permit of the shutting down of certain substations during very light load hours, and in addition they permit continuous operation of the road in case of accident to machinery in any one substation.

Such a system may be amplified by the addition of track switches or even circuit breakers where sub-sections are desired. It is believed, however, that good results will be obtained without either and that the switches without the circuit breakers will usually be all that is necessary. With the system shown in Fig. 9D in mind, it will be well to go into one or two general considerations. First, how big should such sections be? This of course will depend upon several factors, the first of which is the geographical layout of the railroad. This consideration has its effect on the location of substations and the consequent distance between them. Extremely large substations for elevated and subway work should be avoided and consequently this means numerous substations. This belief is founded more particularly on return circuit conditions than on positive conditions. For a substation feeding two tracks and in two directions only, it would seem undesirable to go much higher than 5000 kw. in capacity. Where the feed is in four or six directions,

as may readily occur at junction points, the capacity should not exceed 10,000 kw. This statement of course does not necessarily apply to what are called joint substations, where different classes of surface and elevated or subway loads are handled. Assuming a single line of double-track road served by 5000-kw. substations, it will readily be seen that in heavy elevated or subway service such stations will not be so far apart as to make "tie sections" very long. On the extreme ends of such systems single sections (not tie) should not be permitted to exceed two miles (3.2 km.) in length. This would mean a maximum of four miles (6.4 km.) for "tie sections." Of course with the usual elevated and subway service the sections would be of much less extent, if the size of substations were restricted to 5000 kw. The other restriction on the size of sections is, of course, that of load. Each section should be served by only one circuit breaker per switchboard to give the best results, and it is not desirable in railway service to run circuit breaker sizes much above 4000 amperes, and 3000 is better. The former size will permit of an overload setting of 8000 amperes, which should be ample for any one section.

To summarize, the single sections should be restricted in size to a mean load, during heavy periods, of 4000 amperes, and to a maximum length of two miles.

With sections limited as above, track switches or track circuit breakers would be necessary only when isolation of short pieces of track is required. In subways this feature adds somewhat to the factor of safety to the public, and is even further carried out by providing means so that any motorman or other employee can instantaneously cut off the power by pulling a nearby box or cord. Certain municipalities require sub-division into very short lengths in order fully to protect the public.

In dividing a railroad up into sections, due regard must be given to the point of separation of sections. In general the opening between two sections should not be closed by a car in passing over it. That is to say, one collector shoe must not be on one section while the other shoe is on the adjacent section. With certain types of equipment when trains are "bus-coupled" it is impossible to avoid this. Where gaps between sections are apt to be "bridged" or closed by a car or a train, it is quite essential to keep the voltage the same on either side of the gap. It is desirable so to locate the gaps between sections that they will occur at points where motormen are normally not draw-

ing power. A little care in the selection of gap points will materially improve operation of the car equipment. It is needless to say that from this point of view it is disirable to have as few gaps as possible. In sectionalizing, too much emphasis cannot be placed on simplicity in the switching arrangements, since this makes for speed in handling emergencies.

Complicated track junctions can best be handled as individual sections from the substation. There is always a tower at such places which affords an opportunity to further subdivide the junction through circuit breakers, so that in case of trouble at any given point, the towerman can immediately isolate it. This is of course carrying out the track switch idea to a certain extent.

Construction Methods and Materials

Briefly stated, it is not good practise to use third-rail conductors that are too light in weight, since they are much more difficult to maintain in substantial fashion. Further, it is not good to have third rails that are not reinforced by auxiliary copper. There is a temptation to run up the weight and conductivity of the third rail and not add the copper on certain outlying sections. In such cases, where breaks in the bonds around third-rail joints occur, it will be seen that without the copper to carry the current, a part of a section may become absolutely dead. So that, even if for regulation no auxiliary copper is required, it is a good thing from the emergency side, and even a small copper conductor will be worth while to insure reliability. If such a thing is not used an emergency switch to cut in and obtain a back feed from another section is many times quite worth while.

One of the distinct advantages to be obtained from a system such as Fig. 9c which does not use track switches is, that all the conductivity of the third rail is brought into play as part of the feeder system.

Substation construction for elevated and subway service is almost identical with that for city surface car lines. This has been covered in that part of the report dealing with the latter type of railways.

Return Circuits

This subject is such an important one that it hardly seems advisable to attempt to treat it as part of a general paper on distribution. Furthermore, it seems probable that more definite conclusions on the subject will be arrived at, shortly, than

have been existent before, on account of the combined efforts of the various engineering associations. Suffice it to say that with grounded conductors such as are used in most of the present systems, great care must be used to keep within proper bounds the potential differences along such conductors. This is what makes it essential to resort to small and numerous substations. In most cases it is not necessary to insulate the negative conductors, but with grounded conductors one good way to limit the drop is by the use of insulated negative feeders. Such an installation has a more direct application and is more necessary in subway work than on elevated lines. Certain it is that not enough attention has been paid to the negative circuit in past installations.

APPENDIX VI. DIRECT-CURRENT DISTRIBUTION FOR INTERURBAN AND STEAM RAILROADS

BY W. G. CARLTON

Prior to 1906, practically all direct-current operation on interurban or steam railroads in the United States was at potentials of approximately 600 volts. In general, power was distributed through an ordinary overhead trolley wire, this being reinforced by such additional feeders as were necessary. In a few cases power was distributed through third rails, the arrangement of third rail being practically the same as used on elevated and subway lines in the large cities. There was no electric operation of heavy trains on any of the steam railroads with the exception of the Baltimore & Ohio Railroad, at Baltimore, which operated trains through a tunnel at slow speed and for a short distance.

In 1906 the New York Central & Hudson River Railroad and the Long Island Railroad began changing over from steam to electric service in and near New York City. The Pennsylvania Railroad began electric operation through its tunnels in New York City in 1910 and about the same time the Michigan Central Railroad began electric operation through its Detroit River Tunnel. In all of these cases power was distributed over third rails at approximately 650 volts.

The New York Central and Michigan Central Railroads used a suspended type of third rail, contact being made on the bottom, the rail weighing 70 lb. per yard. (28.5 kg. per m.). The Long Island Railroad used a top contact third rail, weighing 100 lb. per yard. (40.8 kg. per m.). The Pennsylvania

Railroad also used a top contact third rail, but weighing 150 lb. per yard (61.2 kg. per m.). Where necessary, additional feeders were used to reinforce the third rail, and in some cases remote-control switching stations were installed for the purpose of connecting parallel third rails and cables and still being able to disconnect them quickly in case of trouble. With the roads mentioned, power was distributed from substations located from four to eight miles apart.

Railroads using the third-rail method of distribution have found it necessary for locomotive service to install a small amount of overhead third rail or trolley wire over long crossovers. This overhead conductor is not necessary where trains of motor cars are used, as they will span the gaps in third rails at crossovers.

The substation equipment for 600-volt service has not changed materially for several years, with the exception of the introduction of commutating-pole synchronous converters and generators and the use of larger machines. Storage batteries are not being installed to any great extent, and for protection against interruption to service, ample capacity in substation apparatus and in high-tension lines between generating stations and substations is relied upon.

It is not probable that potentials as low as 600 volts will be used for electrification of steam railroads, with the possible exception of those in and near large cities. At the present time the tendency is towards the use of 1200 volts or higher, not only for steam railroads but for interurban roads of considerable length. There are in the United States, 28 railroads operating or preparing to operate at 1200 volts or higher, the maximum voltage being 2400. For all of these roads, the distribution is by means of an overhead trolley, although one of them is using third rail for a portion of its work and a second road is preparing to do so. In general, the catenary type of trolley construction is used.

Power for operation at 1200 volts is furnished direct from steam-driven generators in a few cases, but as a rule is furnished from synchronous converters or motor-generators, these being either 1200-volt machines or two 600-volt machines in series. The only direct-current 2400-volt road in operation at the present time uses motor-generators with two 1200-volt machines in series.

The Butte and Anaconda Railroad installation is an example

of what can be done in handling steam railroad service. Direct current at 2400 volts is used. The trolley wire is No. 4/0 and but two feeders are needed, a 1,000,000-cir. mil for the positive side and a No. 4/0 for the negative side of the circuit. There are two substations 26 miles (41.8 km.) apart. In one direction trailing loads of 3400 tons are hauled, the maximum grade being 0.3 per cent. In the other direction trailing loads of 1000 tons are hauled, the maximum grade being 1.0 per cent.

The general problems of d-c. distribution for interurban and steam railway purposes are here omitted because, except for the weight of train units and consequent details of construction, they are not essentially different from those discussed by Messrs. Gear, Torchio, Rice and Blair, respectively, in earlier appendixes of this report.

APPENDIX VII. A-C. DISTRIBUTION FOR INTERURBAN AND STEAM RAILROADS

BY W. S. MURRAY

In a number of instances attempts have been made to connect cities using direct current on their overhead systems by interurban lines using alternating current on their overhead systems. This necessitated great complexity in the design and control of the motive power equipment to perform the duplex operation. The attempt naturally did not meet with success, as it was clearly an abuse of the application of alternating current. It may, therefore, be said:

That the alternating-current contact wire in general has no application in the interurban field where the equipment must be common to city and interurban operation.

Economics in steam railroad electrification may be looked for and secured by providing a high over-all efficiency from the terminal of the primary transmission system to the drawbars of the trains. Such a system is the one delivering high-voltage alternating current from a single overhead wire, which while doing this also possesses the greatest adaptability and elasticity under the onerous conditions imposed upon it by modern heavy transportation.

By reason of the general acceptance and standardization of 25 cycles, such a frequency in a single high-voltage contact wire, while conforming to a periodicity generally in use, also permits all classes of equipment to operate beneath it, such,

for instance, as single-phase, split-phase, and, through the medium of a rectifier, direct-current motive power apparatus. Therefore, in the case of steam railroad electrifications, in virtue of the above-mentioned facts, it would seem reasonable to offer as recommended practise the use of a single overhead wire furnishing high-voltage alternating current of 25 cycles as the contact system for the motive power apparatus operated thereunder.

APPENDIX VIII. THE RELATION OF DISTRIBUTION PROBLEMS AND SWITCHING APPARATUS

BY E. B. MERRIAM

The principal problems in the distribution of electric power which are affected by switching and auxiliary apparatus may be classified as follows:

1. Maintenance of continuous service supply.
2. Protection against service interruptions due to faults in the distributing system and receiving apparatus.
3. Safe interruption of circuits abnormally loaded.
4. "Safety first" protection for all who come near the distribution system.
5. Operation of the distribution system at maximum efficiency.

Service Maintenance

The maintenance of continuous service supply is usually accomplished by feeding the distribution system from one of several sources of power supply through two or more buses or their equivalent. Connection is ordinarily made between the different parts of such a system by some form of switch in addition to a circuit-interrupting device.

For 250-volt three-wire Edison direct-current systems the switches are usually single-pole, single-throw, edgewise type. They are designed to be arranged in very compact form and economize space so that a large number of feeders may be controlled from a minimum size switchboard. For alternating-current and direct-current switching service at pressures up to 750 volts, it is customary to use the so-called knife blade or lever switch, mounted preferably upon slate and equipped with or without quick break features.

Alternating-current systems operating at pressures above 750 volts are equipped with plain lever switches furnished with detachable handles and usually some form of locking device for

retaining the blade in the closed position against the action of large magnetic forces which are often developed during short-circuit conditions. Up to 2500 volts, these switches may be mounted on marble bases, but above this pressure the best practise demands that the switches be mounted on porcelain insulators secured to iron or steel bases, and located remote from the switchboard.

For direct-current systems above 750 volts, remotely controlled lever switches are becoming standardized. These are usually mounted on porcelain bushings set in slate bases forming part of the switchboard panels.

In some cases, particularly in isolated plants, automatic devices are sometimes installed to connect the house service system with the central station distribution system in case of failure of the isolated plant supply, but such devices have only a limited application.

Service Protection

A means of giving complete protection against service interruptions due to faults which develop in the distribution system and receiving apparatus is now being diligently sought by manufacturers and operators. Their investigations have resulted in the development of numerous schemes for indicating the appearance of faults in the distribution system and for disconnecting faulty feeders without disturbing the healthy ones.

One of the indicating schemes depends for its operation on the unbalancing of the currents in the legs of a three-phase feeder caused by a ground or other fault. The unbalancing induces currents in special series transformers connected to the feeder and gives a visual and audible indication of trouble by tripping a shutter covering the number of the faulty feeder and ringing a bell.

Another scheme, originally developed abroad as a result of suggestions by Kallman and Andrews, depends for its operation on a difference appearing between the current entering at the supply end of the feeder and that leaving it at the receiving end when a fault develops. Until recently, it had not been considered for use in the United States because it requires the use of auxiliary wires to connect the devices placed at the ends of the feeders, and in some designs, special current transformers which may be balanced one against the other. Besides, under

some conditions, it gives no indication of failure of continuity of the auxiliary circuit, which thus renders the protective feature inoperative. It is very sensitive, however, and discriminates accurately between healthy and faulty feeders. It can also be so adjusted that it will disconnect a faulty feeder before the fault gives rise to dangerous circuit conditions.

A modification of the above, which eliminates the auxiliary wires, has recently been developed. This divides each feeder into two parts, placing the parts in the same or in separate cables. The incoming and outgoing currents at the ends of the two parts of the feeder are then balanced through series transformers connected to them, and the secondary circuit arranged as before.

A number of other schemes have been proposed and are in operation, which depend on various kinds of overload, reverse-power and kindred types of relays. The overload relays are usually made partially selective by some form of time delay whose value is in whole or part a function of the overload current. Three principal types of time delay schemes are now available. One depends on the retardation effected by an electrically driven gear train, the electric feature being actuated by the overload current. Another depends for its time delay on the action of a permanent magnet on a disk of conducting material rotated between its poles. A third depends upon the retardation effected by the expulsion of air from a bellows through a fixed orifice.

The reverse-power relays depend primarily on a reversal in the direction of power flow. Numerous forms have been developed in which the solenoid, dynamometer, and induction principles have been employed with more or less success. They all depend on the interaction between current and pressure coils and their range is usually limited by the high minimum pressure at which they will operate without requiring excessive current flow.

Circuit Interrupters

The safe interruption of circuits abnormally loaded presents one of the most difficult problems encountered in distribution.

For direct-current circuits up to and including 1200 volts the carbon-break circuit breaker is applied almost universally with eminent success. Above 1200 volts, however, it has been found necessary to adopt some form of magnetic blowout,

and reliable circuit breakers utilizing this principle have been developed for direct-current circuits up to 5000 volts.

For all alternating-current circuits, with but few exceptions, the oil-immersed circuit breaker is now considered standard. It has been the object of considerable study and research, with the result that its operating characteristics have been markedly improved. The design of contacts, characteristics and quality of the oil, and shape, ventilation and fastenings of the oil vessel have been given especial attention. Further improvements may be looked for in the direction of increased speed of break, better confinement of the oil in the neighborhood of the arc, and an increase in the number of breaks in series per phase.

The duty demanded of oil circuit breakers has, however, been very rapidly increased of late due to the huge generating capacities now being concentrated in single units, and grouped in central stations. The stored energy of such systems has now become so great that it is no longer possible for the oil circuit breaker to dissipate it unaided. Various schemes have therefore been proposed and adopted for assisting in the dissipation of this energy. The first one places reactance in the generator or feeder circuits so as to limit the power which could be obtained on short circuit. This reduces the drain on the generating equipment and in turn reduces the effect of the abnormal disturbance on feeders other than the faulty one. Another scheme introduces reactance into the circuit to be interrupted after the abnormal disturbance has been manifested and before the oil circuit breaker clears the circuit. This scheme reduces the current that the oil circuit breaker must interrupt but does not limit the initial drain on the generating system or protect feeders adjacent to the faulty one. A third scheme introduces resistance into the circuit in shunt with the oil circuit breaker during its operation. This scheme is the only one which increases the energy-dissipating capacity of the modified circuit breaker and appears to represent the most efficient solution of the problem.

Safety First

The protection of attendants and others from injury caused by contact or otherwise with distribution systems is being daily given more attention. To meet this situation, manufacturers have placed on the market lines of so-called "safety

first" apparatus. It has all of the live parts enclosed in iron or steel compartments to which entry is prevented, except when the circuits leading in have been disconnected from the distribution system. These lines include all forms of switching devices from low-pressure, small-capacity, single-pole, single-throw, fused lever switches to complete switchboards, for use on 15,000-volt high-capacity circuits.

Operation Efficiency

The operation of distribution systems at a maximum efficiency requires a minimum investment in feeders and depends for its accomplishment, among other things, on the ability of the various switching and auxiliary devices properly to perform their functions. These devices, together with their limitations, have been discussed elsewhere in this report and repetition here is deemed unnecessary.

Conclusions

It is seen, therefore, that a considerable number of important distribution problems depend for their solution on the characteristics and performance of switching and auxiliary apparatus, and that strenuous efforts are being made to improve the various devices so that they will satisfactorily perform all their functions.

APPENDIX IX. DISTRIBUTION FOR STREET LIGHTING SERVICE

BY PAUL M. LINCOLN

The problem of distributing power for the specific service of street lighting is quite different from that of power distribution for commercial lighting and other purposes. There are two peculiarities which differentiate it particularly from the usual distribution problem. These are:

1. That the area over which the power for street lighting must be distributed, must, at the same time, be served by an entirely separate general distributing system.

2. That all of the power for street lighting service must be switched at certain predetermined periods of the day, being needed only in the hours of darkness.

The fact that street lighting is required only at night makes it desirable that this particular service shall be fed by a separate distributing system, so that the power for use thereon may be turned on and off at will from a single point.

The alternative to the separate street lighting distributing

system is to use the same distributing system for street lighting as for other purposes and to have the street lamps switched off and on singly or in groups at a point near the location of the lamps. This latter alternative presents so many difficulties that it has been used only to a very limited extent, where groups of lamps are located in a small area such as a small park or playground. Where lines are all underground it is usually cheaper to give this service from the general network and switch it at various points by hand than to build separate circuits.

The requirement for the simultaneous lighting and extinguishing of all street lamps led to the development and continued use of the so-called "series system." In this system, all of the lamps of a given circuit are operated in series at a constant current. The amount of current used varies with the type of lamp, from a minimum of about four amperes, with some of the more recent types of lamps, to a maximum of approximately ten amperes, which was the standard when Brush brought out his first arc lamps. Ten-ampere series circuits are also the standard current rating for long-burning flame carbon arc lamps, which have recently been developed and are being extensively used in this country. Approximately 20,000 of these lamps have recently been placed in operation in Chicago. The voltage on a circuit varies, of course, with the number of lamps, reaching a maximum of 10,000 to 12,000 volts in some cases. There are, at present in use, two methods of securing the constant current required by series street lighting systems:

1. The use of a constant-current generator, in which the voltage varies with the load on the circuit.

2. The use of a constant-current transformer, which receives constant-potential alternating-current energy and delivers constant-current alternating-current energy, the potential of which depends upon the load of the circuit.

The constant-current generator may be either direct-current or alternating-current, but practically all arc machines are of direct-current type. It is noticeable, also, that practically the only type of direct-current arc machine that has survived is the so-called "Brush arc machine," which is a direct descendant of the original machine designed by Charles F. Brush back in the days between 1875 and 1880.

The ease of securing constant alternating current by means of the constant-current transformer, together with the general

adoption of constant-potential alternating-current systems for general power supply purposes, has made the use of a-c. constant-current arc service very general. The invention some ten years ago of the mercury arc rectifier has also enabled us to obtain constant direct current from the constant-current transformers, using, as a source of supply, the standard constant-potential alternating-current systems that have now become standard. Therefore, the use of such constant-current transformers in conjunction with rectifiers has largely taken the place of the constant-current direct-current arc machines, and, as time goes on, the displacement of the arc machine by the rectifier will probably become more and more complete.

The advantages of constant-current operation, as compared to constant-potential for the operation of street lights, are numerous. They are so sweeping as practically to eliminate the constant-potential service for this purpose. They may be enumerated as follows:

1. The lamps may be lighted and extinguished from the central station exactly on any predetermined schedule. This is the fundamental requirement that has made necessary the development of a special distributing system for this purpose.

2. Constant-current circuits, as developed at present, have a relatively small ampere capacity (from four to ten amperes) and are available at a relatively high voltage (8000 to 10,000). Consequently, the investment in copper for distribution purposes is reduced to a minimum.

3. The constant-current arc lamp system is inherently stable, whereas the constant-potential arc lamp must induce its stability by means of a series resistance of considerable value. The amount of this series resistance is comparatively large in constant-potential circuits, since it is necessary to operate the arc on available commercial voltages which are higher than required. Naturally, therefore, this excessive resistance decreases the efficiency of the constant-potential arc lamp.

4. When metallic filament lamps are used instead of arc lamps on constant current, we also have important advantages. The filaments of the constant-current lamps are of larger diameter and shorter than those demanded by constant-potential lamps, and, as a consequence, the lamp is not only stronger and less liable to damage but also it is subject to smaller radiation losses on account of the smaller area exposed. This latter advantage is particularly noticeable in the "nitrogen-filled"

lamp which holds out so great promise of future developments.

A system of street lighting which is a compromise between the constant-potential system for individual lamps and the constant-current system is one in which a series of lamps is operated across a constant-potential circuit. In this system 2200 or other available voltage is used to operate a series of metallic filament lamps, each series having a sufficient number of lamps to make the total voltage across the series the same as that of the line.

In order to prevent the breakage of a single lamp interrupting service on the entire series, each lamp is shunted by a special reactance coil. This coil is so designed that it takes but a small proportion of the total current of the system while the lamp is burning. If, however, the lamp filament should break, the entire current of the circuit passes through the reactance coil without danger to the coil. This characteristic is obtained by designing the iron circuit of the reactance coil so that it is operated above the bend of the saturation curve when passing the entire current of the circuit. At the same time, it is possible to obtain a curve of regulation, so that a considerable percentage of the total number of lamps on the circuit may be out of service before the current on the whole circuit is reduced beyond allowable limits. In this system we may see a return to a system which was used at least twenty years ago. The writer well recalls the use of these identical devices in the apparatus that was built in 1892.

This system has the material advantage that it does not require switching service for each individual lamp, but that this service may be accomplished at one point for an entire series of 30 to 35 lamps. Also, it is quite possible to group the switches for a number of circuits at one point. By this means, therefore, the cost of switching may be reduced vastly below what would be necessary if each individual lamp required this service.

DISCUSSION ON SUB-COMMITTEE REPORT ON "DISTRIBUTION OF ELECTRICAL ENERGY" (JUNKERSFELD, ETC.), NEW YORK, FEBRUARY 27, 1914.

H. L. Wallau: The keynote of Mr. Junkersfeld's paper is "centralization." Lack of centralization means a partial or total duplication of land, buildings, equipment and labor. In the proportion that centralization is accomplished, duplication is eliminated and further advantages accrue: (1) increase in the capacity connected that may be served from given equipment, due to increased diversity; (2) reduced investment per kilowatt, due to the use of equipment of larger unit size, and (3) reduced operating expenses.

These benefits lower cost, and as a direct consequence, rates are reduced; and generally they also result in greater reliability of service. A reduction in rates is always followed by a healthy growth in load, and increased reliability of service means much in permanently holding customers.

Other things being equal, one kind of current at one voltage supplied to all consumers would make for minimum cost. This consummation, however devoutly to be wished for, will probably never be realized, as each kind of current supply furnished has a field of usefulness of its own. Improvements in apparatus, such as the 60-cycle converter, will tend to broaden the field of the various classes of service, but it is difficult to imagine the complete elimination of all but one class.

Total centralization up to and including the substation is feasible today. Beyond this point partial centralization must be our aim, and the nearer this can be made to approach unity, the more perfectly we, as engineers, are serving our fellow-men.

In Cleveland we have aimed to centralize as much as local conditions would permit. The transmission system to substations is radial, with two substations in tandem. One cable is installed as a reserve between the generating station and the first substation, and also one between the first and the second substation. Until recently the reserve cable was kept alive at the supply end and the switch at the receiving end was left open. We are at present installing reverse-power relays of the selective wattmeter type on the receiving end of the cables, and will hereafter operate all cables in parallel. Tests show these relays to be very effective, and remarkably free from the limitations mentioned by Mr. Merriam on page 264.

Our reserve capacity under the radial scheme varies from 100 per cent, where one cable is sufficient to carry the total load, to 25 per cent, where four cables are required.

In order to minimize investment, it has been the policy to install originally to the second substation in the tandem group, two 2000-kv-a. cables. When the load has increased beyond 2000 kv-a., a standard 4000-kv-a. cable is installed, and the

two original cables operated in parallel as one, through one oil switch at each end.

In the matter of different classes of service, when possible, both a-c. and d-c. conversion apparatus has been connected to one high-tension bus, reducing the transmission capacity required, because of diversity and improved power factor. This scheme is also followed, as far as practicable, by having one a-c. and one d-c. substation in tandem, reducing the investment in transmission between the generating station and the first substation even more than in the case of two a-c. stations, due to the greater diversity.

Power factor has also been improved by the use of synchronous condensers in substations and on consumers' premises.

The diversified routing of transmission lines has been touched upon by Mr. Gear. This is advisable whenever the investment in subway will permit, but care must be exercised to have the distances approximately equal in order that excessive loads may not be carried by certain lines, and underloads by others.

In the matter of railway load, specific cables are furnished only from the power company's nearest substation to the railway company's substation. Centralization of these stations may come in the future, but the time is not yet ripe for this accomplishment.

General distribution is at 2200 volts, three-phase delta, with single-phase lighting mains radiating from the load center, and three-wire secondaries. The large number of trees in " the forest city " makes this system of distribution much more reliable than the four-wire system.

Tests recently made on weather-proof insulation show that after a small amount of weathering the dielectric strength is less than 2200 volts, but deterioration from then on is slow, the wire withstanding safely the Y voltage to ground. Hence, the liability to electric shock is very much decreased, with the lower voltage.

Small scattered power demands are taken care of by lighting feeders equipped with regulators. Large power is carried on separate power circuits, generally not regulated. The duplication of circuits is not as great as might be supposed, as the factory lighting is carried on the same transformer installation as the power (balance coils being used); and in the manufacturing districts there is relatively little residential or store lighting, so that a No. 6 primary lighting main will often suffice.

Adjacent a-c. substations are, on the average, about 2 1/4 miles (3.6 km.) apart. This compares very favorably with the distances between similar stations in other cities using higher voltages and generally the same size of copper in their feeders.

The maximum 2200-volt load on these stations varies from 1000 to 6000 kw., depending on the district served.

The type of station now standardized is very economical in floor space. A two-story and basement building about 50 ft.

(15 m.) square is capable of distributing a load of 20,000 kw., of which 12,000 kw. may be distributed at 2200 volts and the rest to bulk customers at 11,000 volts. 1500-kw transformer banks, consisting of three 500-kw. self-cooled units, are used. I do not agree with Mr. Gear that, for substations of over 1000 kw., air or water-cooled units are necessarily most economical.

Centralization is further carried out by serving, whenever economically possible, customers exceeding 300 kw. in demand, from 11,000-volt distribution cables with a single voltage reduction at the customer's premises.

Mr. Goodwin has called attention to the equity of charging a lower rate for high power factor and a higher rate for low power factor. A contract has been in force in Cleveland for about two and a half years, which accomplishes this.

Philip Torchio: I would like to ask Mr. Merriam if he can give us some of his actual past experience and data on the effect of the three methods of increasing the rupturing capacity of oil switches, by the use of reactance, especially, and the other method that he referred to, by using the resistance in shunt with the breaker.

S. D. Sprong: I would like to inquire about the experience had with four-wire, three-phase primary distribution. In this system we have the elements of three single-phase distributing lines, and the fourth wire is necessary to maintain the stability of the system. What is the experience in every-day operation, as to the effect of interruptions and short circuits involving the fourth or center wire; as to the unbalanced pressure on the three single-phase systems; and also, in the case of an interruption to the fourth wire, how does that affect the relation of the phases and the circuit as a whole?

D. W. Roper: As far as the short circuits involving the neutral are concerned, they give no particular difficulty. The circuit breaker on that particular phase wire which is involved, opens, clears the short circuit, and the voltmeter compensators are adjusted so that they will maintain the proper pressure on the other two phases. There is a compensator on the neutral wire as well, so that the neutral drop is compensated independently of the drop on the phase wires.

On the question of the neutral opening near the station or some place so as to cause an unbalancing, I do not recall that we have ever had any case of that kind, that involved any great portion of the circuit. There have been cases occurring in the outlying portions of the circuit, which involved a few customers only, but in general the neutral of the feeder, near the station, is a large wire and is generally an underground cable.

On the question of troubles involving short circuits and overloads, we have recently been trying a little heavier setting of the relays, that is, we have been abandoning the idea that the relays protect from overloads. We set the relays so that

they protect from short circuits only, and find that we give very much improved service, without any offsetting disadvantages. We have by the use of the heavier setting cut out such a large proportion of the interruptions due to ordinary overloads or to no apparent cause, that we have a fixed rule that when the circuit breaker opens automatically in the substation twice or more in rapid succession, a patrolman is sent out to find the trouble, and in over seventy-five per cent of the cases he finds the trouble.

E. M. Hewlett: The question of relays has been considered so generally that one might think they were all alike. Many people seem to think that a relay, because it is a relay, will do whatever they desire it to do. Others, however, and particularly those who have made tests of relays on electrical systems, realize that to get proper results from a relay it is necessary to have a rational piece of work for the relay to do, to know the limits of its operation, what it is expected to accomplish, and besides, to have no extra circuits that conflict with the regular operation of the relay and upset the sequence of operation.

Then there are quite a number of systems which have been laid out with the expectation that relays would take care of all the troubles. Now, when the systems are too complicated, that is, have too many side paths, it is difficult to obtain proper protection. A more direct study of the problems involved, of the possible current flow in different directions, etc., should be made in connection with all these relay problems. I believe most of them can be taken care of, but in cases where this cannot be readily done, the system should be changed so that it becomes a practicable system. Some systems are actually impossible for continuous operation, on account of the connections, etc.

In reference to oil switch capacity, which Mr. Merriam brought out, an oil switch can be made for almost any duty, but it is, I think, rather, a question of the amount of energy which it is advisable to connect on any given system. There are magnetic strains in the system which will draw the conductors together and cause numerous troubles, and it depends on how much of a strain you wish to design your system for, how high a duty switch you desire, and how much money you put in the lines or systems. It seems as though 50,000-kw. sections would be about right, but you can run considerably above that with limiting reactances and with feeders so arranged that the energy flow under short-circuit conditions is reduced to a reasonable amount.

I wish to make a point about the so-called "safety first" movement. There seems to be a tendency in some quarters to go to considerable length to protect all circuits that are alive, irrespective of their location or the conditions under which they operate. Many people are of the opinion that *all* live wires should be covered and protected so that they can-

not be touched. Obviously this is going too far. While it is true that great attention should always be paid to the protection of human beings from injury, this idea should not be carried to extremes, and before making blanket decisions in this matter, a careful study of the conditions should be made.

In a manufacturing industry, for instance, there may be employed a thousand or more men to every thousand kilowatts of power used to operate the machinery, and practically none of the men conversant with the danger of touching live electric wires running to the various machines. Here the hazard is apt to be comparatively great, and it seems advisable to go to considerable lengths to safeguard against the hazard prevalent owing to the conditions.

In a central station, however, or wherever the live circuits are accessible only to those expert in their use, and fully cognizant of the danger of contact with them, it appears rather unnecessary to introduce many detail or minute measures of safety. In such an installation the ratio of men to kilowatts may be only one to a thousand, and besides, the chance of injury from accidental contact, in contrast to the manufacturing installation, very small. It thus seems, then, that where switchboards are under trained supervision and kept isolated from others, little further need be done to bring the degree of hazard much lower than it is now.

In reference to 2400-volt d-c. circuit breakers, etc., for railway work, the Butte and Anaconda line has been working quite a while now with a magnetic blow-out type of circuit breaker, but with the magnetic fields on both sides. The same kind of breaker has also been designed for a 3500-volt equipment for a French railway. Enough experimental work has been done on 5000 volts to show that the 5000-volt direct-current circuit breaker is also a practicable device.

H. R. Summerhayes: In Mr. Torchio's paper it is stated that the mains in the Edison three-wire system are always made the same size. I would like to know if experience has shown that on account of burn-outs, etc., it is actually necessary to make the neutral the same size as the outside wires. It is further brought out in Mr. Torchio's paper that, in spite of making the neutral the same size as the outside in the mains, the arrangement of the neutral in the feeders is such that the currents are balanced, and the total neutral copper is only 16.9 per cent as against 83 per cent for the outside wires.

In Mr. Gear's paper some mention is made of systems permitting the operation of cables in parallel to substations, and I would say that if all cables can be operated in pairs a balance relay system is available which will in general give very good protection. Of course, a large installation requires special study to see that all conditions are met. In reference to substations, it is probable that some saving could be made by automatic substations, in the case of the smaller stations.

Mention is also made in Mr. Gear's paper of the three-phase, four-wire secondary network. This is used to a greater extent abroad than in this country, but it appears to have certain advantages. I believe a study would show that it could be used to a greater extent here, to advantage.

Philip Torchio: Where full main neutrals are used they serve as well as feeder neutrals. Besides, the size of the neutral of the mains involves a question of securing a high degree of regulation. To explain: on the side where you have the heaviest load you have the heaviest drop, and, as the unbalanced load will come in on the neutral, if you make the neutral small you will exaggerate the drop on the loaded side. The Edison three-wire system of distribution has been designed with the greatest degree of liberality. While on a railroad system a poorer regulation may be permissible, our system requires very close regulation and, therefore, justifies greater liberality in the use of copper.

John B. Taylor: I ask Mr. Torchio just what he has in mind in referring to difficulties with the diametrical connection of synchronous converters—the diametrical as distinguished from the double delta connection? This diametrical connection has been in regular use in railway service for the last ten or twelve years, and while I cannot speak so well for the lighting field, I know that it has been on lighting converters for at least eight or nine years. The advantages of such a connection are, of course as obvious now as they were at the time of its introduction, and I do not see why there should be any special conditions in the lighting service that should delay for ten or twelve years the adoption of a connection which seems to possess such pronounced advantages over a connection that has been used largely as a matter of chance, I think, previous to that time.

I should like to hear from Mr. Merriam regarding what is, perhaps, a misstatement as to the function of the oil switch in interrupting a circuit. The switch is to interrupt the circuit and the idea is, in addition, to make a switch so that no absorption of energy by it will occur. Unfortunately, it seems to be true, with switches as they are constructed, that it is impossible to avoid dissipating a certain amount of energy in the switch itself, but I cannot see that there is anything inherent that calls for the dissipation of energy in the switch, nor why the switch cannot be so designed that the energy does not have to be dissipated there. A parallel case is when you have water in a pipe. You may have any quantity of energy stored in your reservoir, back of the point in the pipe where you wish to interrupt the flow, and the mere closing of a valve does not necessarily absorb any considerable portion of the energy thus available, and I think, at least on paper, it should be possible to design a switch in which the energy absorbed or dissipated in the switch, at the moment of interruption, could be negligible. Practically, I do not wish to say that we are anywhere near doing that, but it seems to me there is a proper distinction there which should be kept in mind.

On the railway feeders, without going into details, it seems to me that the distribution network must meet two conditions. The first condition is that the railway trolleys, feeders, third rails, etc., must be more or less interconnected in order to work the conducting material at a fair economy, and also it must be possible to have them separated so that under operating conditions a short circuit at one point will not tie up things too extensively. This, of course, results in the various feeder systems, various devices for switching feeders, circuit breakers, etc., which must be placed along the line.

I see no specific mention in any of these papers of the use of the so-called "automatic sectionalizing switch"—a device which may be put on the line to tie together two feeders or sections of trolley wire or third rail, both of which are alive. These switching devices connect together two or more feeders, provided they are separately energized from the same or different substations, and in case of a short circuit, or in case of a desire to interrupt the power, merely by interrupting power supply to both feeders, at the substation or at the power station, these disconnect themselves, at which time power can be restored on one without restoring it on the other. Of course, this scheme is not universally applicable, yet there are so many cases where it would effect such marked saving in copper that it would seem to merit more specific mention.

I want to raise a question in connection with what Mr. Murray has to say about the single-phase distribution. The principal point he mentions is the one-wire single-phase railway transmission system. If we can believe the evidence of our eyes in riding over the New Haven road, it is clear that a change in that distribution system has been made, or is in the process of making. I trust Mr. Murray may have something to add on this point to reconcile the discrepancy between what is done, or done in part, on the representative single-phase road, and what he states is the desirable way of doing it.

Mr. Lincoln, it seems to me, has missed the real reason for the series lighting system. I do not think that the desirability of throwing the switch on at the power house to turn on all the lights on the street is by any means the controlling reason which brought about the series system. The series system came about through the inherent characteristic of the carbon arc, the property which has been commonly called "negative resistance", which meant that it was necessary to have controlling devices to keep the current within a proper value, and it was a much more economical proposition to do this either by the design of the machine at one point, or other controlling means, at a central point, rather than by individual steadying means at the lamps. Also we should remember that the arc light started as a d-c. instead of an a-c. system, so that it would have been out of the question to distribute at low voltage with an economical amount of copper, and out of the question to distribute at high voltage without

inserting the necessary transforming devices for individual lamps. So far as the d-c. arc is concerned, these conditions seem still to control.

The point I want to make is that the series system came in for good and sufficient reasons, which are other than the desirability of turning lights on and off at one time.

At the present time, with the ability to run tungsten lamps of high candle power on alternating-current circuits quite as well as on direct-current circuits, it looks as if the separate series circuit with the separate cables or ducts from the generating station had little excuse for continuing as the only street lighting system.

E. W. Trafford: With reference to Mr. Lincoln's paper on arc lighting distribution, I want to say that a few years ago, in a station which now has about 2000 arc lights, I saw that we were filling our streets with a large number of small wires, and recognized the desirability of reducing the number of wires and using those of larger size. A great many years ago a system was devised which made use of constant-current distributing transformers. I have used that system for the past three years with considerable success, with circuits of 200 arc lights, using 30 amperes constant current at 4000 volts.

Instead of distributing current single-phase, a three-phase star connection with series transformers in each leg may be used, in which case, with the same current and voltage, the circuit would be of 250 kv-a. capacity. Such a system has many advantages with both overhead and underground distribution, perhaps more noticeably for underground distribution, where a few cables of convenient size can be placed in the ducts in place of the multiplicity of small cables usually employed. The system also offers great advantages in a mixed underground and overhead distribution. It is easy with this system to install a transformer and drop underground at any point and operate a separate series circuit of the desired voltage and current.

Instead of using constant-current regulators or transformers as they have heretofore been used, they may be employed merely as regulators in connection with ordinary static transformers. With a number of transformers on a given line it is improbable that all of the secondary circuit would open at one time and consequently the same percentage of regulator capacity is not necessary. By this means the power factor of the system can be very much improved.

In the station the substitution of a few devices of moderate capacity in place of the multiplicity of small apparatus results in a simplification of switchboards which is very apparent. In some cases, as in the one cited, the use of this system eliminates the necessity of a substation.

Objection to such a system in the past was based on the fact that transformer design was not as well understood as it is now, and that, upon the secondary circuit becoming open, a large rise

of potential would follow, causing burn-outs or establishing a dangerous condition upon the secondary circuit. But in these days of automatic devices it is very simple to arrange automatic switches which short-circuit the secondary, either upon a rise of potential occurring or upon the interruption of the secondary circuit. In the installation referred to, twenty-five transformers have been in service for about three years, without difficulty or the loss of a single transformer.

With this system it is possible to run a few well-insulated supply mains throughout the length of a city, and at convenient points install transformers operating short series underground lines, at moderate voltage, thereby making it commercially practicable to furnish underground street lighting service even in communities of moderate size.

J. T. Kelly, Jr.: There are one or two things which we are doing in Baltimore, that, from the standpoint of the operating engineer, may be of interest to some of you gentlemen.

For the reason that has been mentioned several times, we are in the position of having to furnish as near absolutely perfect service as possible. One of the troubles which we have experienced is that of feeder interruptions. The induction motors, even though the feeder may be restored in a very short length of time, will drop out and we have some complaints from customers on that account. It has been thought that if the feeder could be restored to service quickly enough, that trouble could be obviated. Experiments have been carried on with an auxiliary relay of the wattmeter type which operates to close the feeder switches as soon as they open, and it has been found that, with reasonable certainty, the switches can be closed within seven-tenths of a second from the time they start to open, or, putting it another way, on 60-cycle service, well within 40 cycles, and that there will be practically no rush of current to the induction motors, no interruption to the service, and as far as the lighting is concerned, merely a very slight flickering. This was the idea of our Mr. F. E. Ricketts, who has carried through the experiments and reached the point where the system is about to be put in operation in one of the principal substations.

It will also have a very important use in outlying substations in the suburbs at which an operator is not ordinarily in attendance. I ought to say, in that connection, that these relays may be so set that they will close a circuit once, and if it drops out again, remain out, or they may be set to close the circuit two or three times, or as many times as you like, before remaining out.

The question of locating faults on underground cables is always a very troublesome one. It came to our attention, through our friends of the local telephone company a year or more ago, that certain of our frequency changers, operating at 2300-4000 volts, had such characteristics that there were present,

in the neutral, harmonics which caused a disturbance on the telephone lines. A study was made, and it was found that the thirteenth harmonic was present to that extent, and steps were taken to change the characteristics of these machines. The idea occurred to some one, however, that that might be made use of in the locating of underground cable faults, and it has been made use of. The method is to connect a machine having this characteristic in a marked degree to a spare bank of transformers, preferably of large capacity, and connect the faulty cable in series with the neutral between the machine and the transformer bank. If the cable is broken down between conductors, a dead short circuit, two conductors may be used; if it is broken down to ground, one conductor and the lead sheath may be used. Since we are trying to get rid of that characteristic in our machines, it was necessary to rig up a small set, of about 5 kw. capacity, which we ordinarily use for that purpose with much success.

The method of finding the fault after the connection is made is by means of a small finding coil in series with a delicate telephone receiver. It is only necessary to go into the manhole and hold the finding coil close to the cable. If you are between the station and the fault, the harmonic is present, and you readily hear the tone in the telephone receiver, which is a very different tone from the general tone of the system, and readily discernible. The moment you get beyond the fault, you fail to hear the tone.

John Murphy: I have read of such a scheme being employed in Berlin, and a friend told me that it was not necessary to enter the manhole. The sound is detected walking along the street. I would like to ask Mr. Kelly if he has heard of that system or used it.

J. T. Kelly, Jr.: On our distribution feeders we have adopted the method of placing an expulsion type fuse between the main feeder and practically all the principal taps from the main line. These have the advantage of acting as disconnecting switches, if desired, as well as of clearing the main feeder of trouble, instantly, when trouble occurs on one branch.

Our company has spent considerable money to perfect a system, both in the overhead and underground portions of the a-c. territory, of tying in adjacent feeders through oil switches at as many points as possible, within reason. We use oil switches in every case, properly phased out beforehand, and in connection with this scheme we furnish each of our trouble men with a small pocket-size loose-leaf binder, carrying bulletins of various information, and many other things, including diagrams of the emergency connections of each feeder, so in case of trouble it is not necessary to get hold of some one who may be familiar with all these points, or may be familiar with the record of them. Each trouble man has in his pocket the specific direction which will enable him to restore service in the

shortest possible length of time. At frequent meetings the trouble men are coached and quizzed on these points to see that they are kept in mind.

There is another point in connection with that—the tying in of feeders on the outside may be considered in the light of a station switch of which the station operator has no knowledge. We have found it a very wise thing in every case to advise the station operators, in advance, of such and such a switch, so they may know what to expect, otherwise the performance of their instruments, regulators, etc., may be very misleading to them.

I notice the statement which was made in regard to the Commonwealth Edison Company, that in case of a short circuit on one phase the breaker on that phase will open and the other phases remain in operation. We have not been able to do that, with success, for the reason that we have a great deal of three-phase load on our distributing feeders, and we have found that, when we attempt to operate two phases of a four-wire feeder, the third wire being dead-grounded or short-circuited with the neutral, we blow the fuses on our three-phase banks of transformers and get into a good deal of trouble. Our breakers are therefore locked so that they operate together.

H. B. Gear: Answering Mr. Kelly's question, the difficulty mentioned is avoided in the Commonwealth Edison system by not connecting the neutral of three-phase installations to the neutral of the system. When this is done trouble on one phase cannot be communicated through the transformers to the other two phases. This has entirely remedied this sort of trouble, in Chicago.

Carl Schwartz: The distribution of electrical energy in a certain territory is a natural monopoly. Competition is bound to lead to a duplication of facilities, resulting in less density of load per unit and a less favorable diversity factor. This condition also suggests pooling existing facilities. Any wastefulness in this respect, as well as in the design or development of a distribution system, will ultimately fall upon the public, either the company's stockholders or the consumer, who will have to pay a higher price for the product. When it is further considered that the cost of power at the busbars of the power station is generally below the fixed charges, operating and maintenance expense for its distribution, it will be seen that the economics of distribution deserve careful attention.

The distribution system of one of the railroad companies in New York City was designed after a complete analysis of practically all possible combinations of feeder connections and distributions of substations in order to arrive at the most reliable and economical combination. The system can be briefly described as follows: Primary three-phase alternating current at 25 cycles is distributed from two power stations at 11,000 volts to nine substations located from about 3.8 to 8.6 miles (6.1 to 13.8 km.)

apart, delivering direct current at about 660 volts to the third rail. Seventeen high-tension lines connect the two power stations directly with the substations, the latter being interconnected by tie lines.

All substations are supplied by not less than two independent lines and are equipped with three or four synchronous converters of either 1000, 1500 or 2000 kw. capacity, and in some cases, where continuity of service is of prime importance, with storage batteries. The direct-current feeder system connects the substations to the third rail through circuit breakers under remote control from the substations. The third rail is sectionalized throughout by the circuit breaker connections, the breakers being installed in thirty-two separate buildings, located from about one-half to two and one-half miles (0.8 to 4 km.) apart throughout the electrified territory, which extends over a total distance of about 51 miles (82.2 km.). The fixed charges, operating and maintenance cost of this system, including storage batteries and third rail, are, with the cost of current at the power stations busbars, in the ratio of about 1.3 to 1, which shows that this distribution system for d-c. railroad operation is economically designed.

The engineering features of a distribution system are so closely related to the generating system and its location, and to the distribution and character of the load, that a determination of the distribution system alone, without due consideration of all other portions, will lead to erroneous results. One system may permit the generation of current more economically and with a greater degree of reliability than another. For instance, large quantities of electricity are produced and distributed under more favorable conditions in the form of three-phase current than in the form of direct current or single-phase alternating current. At the point of consumption alternating current may be acceptable under some conditions and not under others; for instance, dense city service for light and power practically demands the insurance of continuity of service by storage batteries.

The efficiency of the distribution system alone, from an investment, operating and maintenance standpoint is, therefore, not conclusive evidence of the wisdom of its selection, as its advantages may be counterbalanced by disadvantages incidental to the generation and application of the product. Hence, a proper comparison can only be made by analyzing from the coal pile to the point of delivery, whether the ultimate form of power be light, a motor pulley, the drawbars of a locomotive, or something else.

Appendix VII, on a-c. distribution for interurban and steam railroads, differs from the others in that it does not illustrate present practise, but offers the use of a single a-c. trolley wire as recommended practise. If this question was as simple and easy to answer as done in the paper, probably many of us would be thankful to Mr. Murray for the relief from a good deal of work.

The speaker does not wish to be understood as wanting to

detract in any way from the merits of the system Mr. Murray advocates, as it may, under certain conditions, produce results equally as good as or better than others. It is noted, however, that in drawing his conclusions Mr. Murray omits any reference to the matter of current supply and its complications, and apparently overlooks the fact that other forms of current on a trolley wire will likewise give satisfactory results, and will even avoid the necessity of carrying some equipment of the distribution system on the locomotives. If Mr. Murray should ask for a quotation for the delivery of single-phase power for railroad service, he would probably find that he has to pay an appreciably higher price than for three-phase current.

Mr. Blair refers to the important matter of electrolytic action. This question has been given very careful consideration by one of the railroad companies in New York City during the past few years. Exhaustive measurements of current and potentials have been made and recorded to determine the flow of current in steel structures, cable sheaths, pipes, etc.

A system of protection was developed which has made the structures likely to be affected as free from electrolytic action as possible, and it has been determined by laboratory tests and field investigation that the slight amount of current flowing is either too small for any appreciable effect or it has been so directed as to be inactive.

Insulated negative return feeders contribute to the prevention of destructive electrolytic action, yet, unless they are so connected as to produce fairly uniform pressures at the track, they do not bring about the desired result. To accomplish this, the loss in the feeders has to be balanced either by resistances or by boosters, and the cost of the insulated negative system thus increases rapidly with an increase in uniformity of pressure.

The subject requires considerable study from case to case to determine whether this system, or other methods like the drainage system, or a combination, is preferable. Structures can frequently be sufficiently protected by directing the flow of current so that they are negative to the running rail, and this method has, to a large extent, and successfully, been followed in the case to which I have referred.

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RECORDING DEVICES

BY CHARLES P. STEINMETZ

ABSTRACT OF PAPER

The author calls attention to the importance of keeping records in electrical systems and points out that proper records can be secured only by automatic recording devices, largely because of the uncertainty of the personal element in times of accident or stress. The three types of recording devices in general use are those having a revolving disk, those using an endless tape or photo-film, and the multi-recording device on which no record is made of normal operations and on which the record sheet moves only when a record of abnormal occurrences is being made. The revolving disk machines produce such condensed records that a sequence of rapidly fluctuating events cannot be distinguished, while the curve-drawing instruments, if the tapes were run rapidly enough to show all the fluctuations, would produce records of such enormous length that they would be impracticable to operate commercially. With the multi-recorder the record is made in a very condensed and handy form and its accuracy in respect to time is very high, so that the sequence of events recorded can be checked within a fraction of a second. The latter instrument, therefore, is adapted to produce minute and accurate records of all phases of station operation.

WHILE the keeping of records is essential in any business, it is especially important in the operation of electrical systems, and thus records have always been taken of voltage, current, power, of the time of starting or stopping generators, etc., in electrical systems.

Perfect reliability, however, can be secured only by automatic recording devices.

For instance, where it is the duty of the station operator to keep constant voltage, the voltage record made by noting down the voltmeter readings at constant periods of time would probably show uniformity, while an automatic recording device may show bad fluctuation between these times. A protection against neglect or carelessness of taking records, and a check on the operating force, is afforded only by automatic recording devices. But especially when things go wrong, when accidents happen, and the necessity of action interferes with careful ob-

servations, the human machine more or less breaks down and only automatic devices are reliable in recording the events.

Automatic recording devices are therefore extensively used: Revolving-disk recording voltmeters, ammeters, thermometers, steam flow, meters etc.; curve drawing instruments; the oscillograph.

In the revolving-disk recording meter, a 24-hour, or 12-hour record is made on a circular chart. The shortest time interval, which can, under industrial conditions, be accurately noted on these instruments is not much less than a quarter of an hour. Where the quantity changes slowly, as the temperature of a room, a clear chart is given. Where, however, more rapid fluctuations occur, as with current and often with voltage, the chart shows only a broad blur, and neither the individual variation nor the sequence of events can be seen, but merely the maximum and the minimum values estimated.

Curve-drawing instruments, in which an endless tape moves with greater or less rapidity, in front of the recording pen, are used for records of more rapidly changing events, as current, voltage, speed, acceleration of a rapid transit train cycle, etc. But to take a continuous record of an interurban railway substation by a curve-drawing instrument moving with sufficient rapidity to show all the fluctuations, would be feasible only in special investigations; but the enormous length of the record would exclude it in commercial operation.

One of the most rapid recording devices is the oscillograph, and its use has been of material assistance in electrical development, for instance in giving information on momentary short-circuit currents of alternators, on the performance of circuit breakers and other problems, upon which information could be derived in no other way. But the taking of a continuous record of station operation by oscillograph obviously is out of the question.

While automatic recording devices are necessary in the normal operation of electric systems, they are still much more essential under abnormal conditions, when things go wrong, and accidents happen. Usually no serious difficulty exists in designing apparatus to operate satisfactorily under normal conditions; also no serious difficulty exists in operating a system under normal conditions, but to meet the abnormal changes of accidental conditions is the serious problem of the electrical designer and of the station operator.

We really know relatively little of the abnormal conditions which are met in electrical operation, and most of our knowledge is rather theoretical, representing what might happen; but exact information of what actually happens is extremely limited. When some accident happens, whether it be the failure of a transformer, or the shut-down of a big system, usually an investigation is made, reports called for, and the witnesses cross-examined. But the information gleaned from these examinations is practically always unsatisfactory and incomplete. Frequently no trained observer was present, or so many things happened almost simultaneously, that most of them could not be observed. The circumstances are very unfavorable for exact observation. The necessity of immediate action excludes close observation and almost always excludes immediate

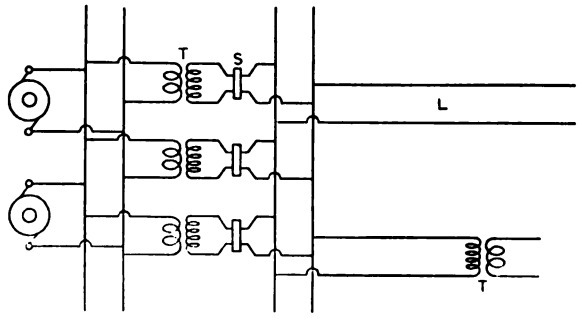

FIG. 1

noting of the observations, so that the record must be based on the memory of the observer, which is not very reliable in times of excitement. The personal element also comes in, the natural tendency toward avoiding personal responsibility for the accident. The sequence of the events, which is all-important for the understanding of their cause, is rarely noted in the excitement, and thus such examination hardly ever definitely fixes the cause of the accident, without the necessity of very extensive guessing of more or less questionable reliability. It is, however, of the greatest importance to the operator as well as the manufacturer of the apparatus, to know exactly what happened, so as to guard against its recurrence, and to fix the responsibility.

For instance; in a large high-voltage transmission system, partly illustrated diagrammatically in Fig. 1, a big transformer *T* in the generating station, a high-tension switch *S* in the gen-

erating station, and a transformer T' at the end of a branch line, are destroyed. At the same time a flash-over occurs on the transmission line L.

Postmortem examination of the transformer showed numerous arc burns on coils and on the tank, and the coils badly deformed and bent out of shape. Questioning of the operators elicited the information that lightning had been frequent during the period preceding the accident. One operator believed he had noticed static in the station for some time before the accident. It is suspected that numerous short circuits have occurred in the lines during the weeks preceding the accident.

This information is altogether too meager to find out beyond doubt what actually happened. We can only theorize what may have happened, for instance:

1. An arcing ground occurred on the line L, producing moderately high frequency—a few thousand cycles. This lasted for some time, possibly hours, until the high frequency broke down somewhere, either by electrostatic heating of the insulation, or by the continual impact of the oscillation. It broke down to ground in the station transformer T, and thereby caused a short circuit through transformer T and line L. The high-tension switch S, in attempting to open this short circuit, failed, due to the excessive current and the superposed high-frequency oscillation, burned up and so created a dead short circuit at the transformer terminals. The mechanical magnetic forces resulting therefrom in the transformer, moved the coils. The shock of the short circuit broke down the transformer T' at the end of the branch line.

2. Numerous flash-overs had occurred during the preceding weeks in the transmission lines, resulting in heavy short circuits. While the transformers were strong enough to stand occasional short circuits, the short-circuit stresses were so enormous, that continual short circuits gradually impaired and finally broke down a transformer T. This resulted in the destruction of the circuit breaker S, the failure of the second transformer T', etc.

3. Lightning entering the line L started a high-frequency cumulative surge in the transformers, producing spark discharges between the coils. The same or another lightning stroke flashed between the lines, caused a short circuit, resulting in the destruction of the circuit breaker. The spark discharge in the transformers finally led to short circuit, which distorted the transformer coils.

4. An internal oscillation in the transformer, due to entrance of high-frequency lightning, or resulting from an arcing ground on the line, caused spark discharges in the circuit breaker, leading to its destruction. The short circuit resulting therefrom, moved the transformer coils and brought them sufficiently near to either end of the tank, to cause arcing over, with the resulting destruction of the transformer.

Numerous other combinations of the phenomena could still be devised, to account for the accident, for instance, the transformer T' at the end of the branch line may have broken down first, and the accidental arc may have produced the high frequency, which damaged the circuit breaker and main transformer, and flashed over the transmission line, etc. But whether the trouble started with a high-frequency oscillation in the transformer, or resulted from a high-power short circuit, or from lightning, or from an arcing ground on the line, or from a combination of two cases, as high-frequency oscillation and short circuit, cannot be learned from the available sources of information. Neither can it be determined, whether the transformer was mechanically too weak to stand a short circuit, or whether it was weakened by frequent short circuits combined with high-frequency disturbances. It is, however, ofi mportance to the manufacturer to fix the responsibility, and to know whether the transformers are mechanically too weak and should be made stronger, and correspondingly more expensive, or whether and what additional protective devices should be developed. And it is of still greater importance to the operating companies, to take such steps as will insure reasonable reliability of operation.

If automatic recording devices would show what happened and the sequence of the happenings, whether the trouble started with lightning, or with an arcing on the line, or a line short circuit and how this originated, or a transformer surge in the generating station or the branch line, etc., then in most cases the phenomena could be exactly determined, and with reasonable certainty precaution against their recurrence taken. Also, less difficulty would usually be experienced in fixing the responsibility on the manufacturer of the apparatus, or on the operating engineer, or on *vis major*. As it stands at present, the transformers are rebuilt with greater mechanical strength, and damping devices against transformer surges installed, and it is "hoped" that the phenomena against which these guard,

were the causes of the trouble, but we cannot possess the confidence that the same will not happen again, and if similar troubles do occur again, it merely means that some of the other various possibilities were the initial cause of the trouble, and that the remedy would lie in the installation of an arcing ground suppressor, or in grounding the neutral, or in disconnecting the grounding of the neutral, or in reducing the sag of long spans to eliminate the swinging together of the lines, or in adding another disk to the suspension insulators, or in better weeding out defective insulators by high-frequency testing, etc.

Numerous such instances could be given. Thus, in underground cable systems, breakdowns occur frequently in groups, or practically simultaneously, and it is difficult to determine which cable started the trouble. For some time, often days, troubles with feeders may have preceded the breakdown, and if properly recorded, would explain its cause and so give a greater probability of guarding against its recurrence, etc.

The difficulty or impossibility of getting complete and exact records of what happens in electrical systems, and of the sequence of the events, is the most serious limitation, at present, to providing protection for such systems.

Automatic recording devices thus are of the greatest importance for the safety of operation of a system, especially where reliability is important. However, in case of trouble, the sequence of events commonly is so rapid, within seconds or less, that such devices must be capable of recording within fractions of seconds. The dial instruments, like the revolving-disk recording meters, therefore, are out of the question, as they show everything within a few minutes as simultaneous. Curve-drawing instruments would have to run the tape rather rapidly. If we assume that 50 records are needed, and allow between $\frac{1}{8}$ and $\frac{1}{4}$ in. per second as the minimum, about 15 miles of tape would be unrolled per day, and to look all this over to see the records, obviously is impossible, especially when it is desirable to go back for weeks to see what has preceded. With phenomena like lightning, where several strokes may occur in one minute, and then no record for weeks or months, obviously any recording device with continuously moving tape is impracticable. Where records are made at more or less infrequent intervals—sometimes, as with circuit breakers, at fairly regular intervals, and sometimes, as with lightning discharges, at very irregular intervals—an instrument in which the tape

does not continuously move, but, as in the typewriter, moves only when making a record, is essential.

To give reasonably complete information on the station performance under normal as well as abnormal conditions, records are required of the closing and opening of every circuit breaker, of the operation of the lightning arresters, of the appearance and duration of high frequency in the lines, of grounds and short circuits, possibly of excess currents, of over-normal and subnormal voltage, frequency, etc., etc. Considering then, that even a small station may connect two or three lines, and each line has three phases, and a separate record of each phase is necessary, it is obvious that a considerable number of records is needed. With a stationary record sheet, moving only whenever a record is made, 50 records can easily be taken on the same sheet, and a 50-point multi-recorder thus appears as a convenient unit. In such a device, a sensitivity of at least $\frac{1}{4}$ to $\frac{1}{2}$ second is desirable, so that phenomena following each other at intervals of $\frac{1}{4}$ second or more, are separately recording, while everything which occurs within $\frac{1}{4}$ second appears as of the same time. Such high sensitivity is desirable to get the sequence of events which to the observer may appear simultaneous, as the breakdown of a number of feeders, etc. At the same time, such great rapidity of action requires a powerful mechanism, and, considering that the operating mechanism must be capable of working very many thousand times without failure by wearing out, the problem in the development of such an automatic multi-recorder was rather a difficult one. Also, when a record comes in within less than $\frac{1}{4}$ second from the preceding one, while the record sheet is still moving in receiving the previous record, the second record would blur, and this difficulty thus has to be overcome by retarding the second record until the taps have come to rest.

On such a multi-recorder print, one record point should be reserved for recording standard time at fixed intervals, thus giving the time correction of the clockwork which operates the recorder, so as to make it possible to record the sequence of events occurring almost simultaneously in distant stations and noted on different multi-recorders.

A description of this instrument is given by Prof. E. E. F. Creighton, in the A. I. E. E. TRANSACTIONS, Vol. XXXI, 1912, p. 825.

Discussion

Charles L. Clarke: Dr. Steinmetz has referred to the taking of continuous records by the oscillograph or other curve-drawing instrument, in which a photo-film or a paper tape is reeled off at a constant speed to maintain uninterrupted the time-element of the record, and he has in general called attention to the obvious impracticability of using an apparatus of this character adapted for recording events that may happen at quite widely separate times, such, for example, as the normal switching operations in an electrical system, and which, furthermore, is adapted to record with sufficient accuracy as to time, a very rapid sequence of events, such as a succession of operations by automatic switches brought about by abnormal or accidental circumstances, or which will at least give a definite indication as to which event happened before all the others of the sequence.

We are, nevertheless, generally accustomed to curve-drawing instruments in which the time record depends upon the constant progression of a tape, or its equivalent in the form of a rotating paper disk. But in order that the record may not be of practically immeasurable size and commercially out of the question, sacrifice of close accuracy in the time record has to be made by running the tape at a very slow speed. Thus a rapid succession of recorded events is merged indistinguishably together as if but one event had happened, and naturally there is no way of finding out which occurred first.

In the multi-recorder a radical departure from the old way of continuously recording time by constant motion of a tape and superposing thereon the happening of other events, when they happen, has been made, and in its place has been substituted the method of simultaneously printing upon the tape when at rest, the occurrence of a particular event and the time at which it takes place, followed by a slight progression of the tape to receive the record of the succeeding event and time it occurs, and so on.

This is all the record that is needed, when vital events to be noted are not of a continuous or flux character, but take place at definite and recurring instances of time, as, for example, in switching operations, for recording which the instrument before us was primarily designed. The record is kept without the use of an inordinate length of tape and is in fact in a very condensed and handy form; nevertheless, accuracy in respect to time is insured to a very close degree. This is the fundamental merit of the apparatus, which has in this instance been reliably put in practical form by skilful attention to mechanical and electrical details.

The applications of the multi-recorder that are apparent are many, and numerous other uses for it will doubtless be found from time to time.

In the paper describing the device, published in the A. I. E. E.

TRANSACTIONS, Vol. XXXI, 1912, p. 825, abundant evidence is given of its value for recording switching operations in an electrical system. The record made under normal conditions is a watch over the proper performance of duty by the switchboard attendant, while under accidental and abnormal circumstances the instrument not only stands guard over the attendant to record his correct moves, or his blunders, but may be adapted to pick up and record the shortcomings of the system in respect to the matters that are outside his jurisdiction, or his ability to control.

Its action is so rapid that the sequence of operation of oil switches can be noted. Time-element relays can be checked to the nearest second. Duration of accidental short-circuits and surges can be recorded. It notes whether a feeder is alive, and if so, the time when, and initially from which end, it was energized. It may keep watch over the care of aluminum lightning arresters in respect to charging them properly and at correct intervals, and that they are not abused by charging them for too long a time. The connections of the multi-recorder can be used to make the load dispatcher's dummy switchboard in a power station automatic. More rapid switching can be carried on, as the exact conditions are always before him. Signals and responses from one part of the station to another can be recorded, also starting, synchronizing and stopping generators, operation of ventilating motors, and various auxiliary apparatus. Determination of the value of the overhead ground wire of a transmission line by recording the lightning strokes (ordinarily recorded by puncturing paper) is feasible, in which application the instrument would take the place of a large corps of observers located along the line, and with elimination of the confusing uncertainties of many observations tempered by the personal equation of different individuals. Its reliability and utility in practical service have already been fully demonstrated for those of the foregoing purposes to which it has been thusfar applied.

The probable utility of the multi-recorder in automatically noting the time and duration of application of successive steps in manufacturing processes suggests itself; it might be a process for making insulating material, requiring exact intervals of application of current potential and heat, or processes in a chemical works, or in refineries, etc. It might be applied in boiler rooms of large power stations to check the testing of gages, the opening and closing of valves, dampers, firing operations, etc.

The operations going on in railway switch towers at important crossings and at large yards and terminals are easily within the ability of the instrument to record; likewise record may be made at headquarters of the calls from police telephone and fire alarm boxes.

Tally can be kept on the operation of some machine tools,

for instance, punch presses, to insure that the normal output is forthcoming.

The time when employees come on and go off duty can be centrally recorded.

We have before us the 24-hour power log of a cement manufacturing company, in the form of a large sheet ruled off vertically for time, and horizontally for apparatus, and for various other data, the record of which is to be noted each hour. The record for "apparatus in operation," includes engine-driven generators, exciters, air compressers, condensers, pumps, stoker engines, boilers, and fifty-one motors; there are also places for record of load curve, wattmeter readings, general data, miscellaneous readings, coal data, and crews on duty.

This log is filled in daily by hand. The record for all the apparatus noted above could be made by a multi-recorder, and also that for the crews on duty. The application would in this instance be easy, and not necessarily call for an automatic electric contact device on the apparatus to cause a record. The duty of the man on the job would simply be to press one electric button when an apparatus was started, and press another when it stopped. This I believe would insure proper attention to duty in most cases. The man would know that his record was made beyond his ability to alter it, when he pressed the button, and he would be likely to see to it that the record was made at the right time. If, however, circumstances should make it important to record the operation of apparatus beyond any doubt, a suitable electric switch device could be applied thereto; this would absolutely prevent tampering with the time recorded. The log now used presents every opportunity for tampering, to the extent that the operative learns from experience what can be done without detection; it also offers a chance for errors resulting from not making a record at the proper time, but neglecting so to do and trusting to memory to fill it in at a later time. The face of this log is an additional suggestion of possible fields for the commercial application of the multi-recorder.

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THE PRESENT STATUS OF ALUMINUM-CELL LIGHTNING ARRESTERS

BY E. E. F. CREIGHTON

ABSTRACT OF PAPER

This paper gives a brief survey of the conditions of operation of aluminum-cell arresters, without any description of the forms of the arresters. References are made to recent investigations of lightning phenomena and their possible effects on the design of protective apparatus used at present. The d-c. aluminum arrester is most economical and represents the highest possible grade of protection. In connection with the a-c. aluminum arrester the following points are discussed: dielectric spark lag, dissolution of film, charging resistance, oscillations, damping, degrees of surges due to natural operations and accidents, and insulations which withstand these surges. Charging resistance on aluminum arresters is chosen to make surges harmless, and the charging resistance gives great immunity from damage to the arrester itself by any accidental and temporary local condition in the arrester. In conclusion, the aluminum-cell arrester may justly be regarded as a standardized electrical device founded on solid fundamental principles.

ALTHOUGH the aluminum-cell lightning arrester is now many years old in practise, there is available in the TRANSACTIONS of the Institute very little definite scientific information on this subject. It has seemed preferable to produce certain results rather than describe beforehand how such results were to be obtained. The practise of the aluminum arrester has now settled down to definite sets of conditions, and it is the object of this paper to consider standard conditions and open up the subject to discussion. Aluminum lightning arresters will be treated in general on points that may seem debatable. No detailed description of apparatus will be given herein.

The question is often asked—Will certain types of arresters be superseded? In very few cases has it been possible to give a definite answer to such a question, owing to incomplete knowledge of cloud lightning phenomena. It has been possible to say that if future investigations of cloud lightning prove that every lightning stroke is of high frequency and steep wave front,

certain changes would come about under these conditions; it would be possible to prophesy, with considerable confidence, that many types of lightning arresters now in use would disappear. The natural growth of protection would be along the line of various types of high-frequency absorbers.

If, on the other hand, it should be shown that lightning is always of low frequency, and gives the surge a sloping wave front, then again, it would be fairly safe to prophesy the contrary—that very few of the lightning arresters now in use would disappear, and that probably no other devices would take their place.

Recent investigations of lightning phenomena have confirmed our views that cloud lightning has wave fronts of various degrees of steepness, and without question some of the lightning strokes are not high-frequency effects but are of the nature of simple impulses. The writer's recent experiences along this line have been gained by indirect methods. Lightning arresters have been put out which were sensitive to very high frequencies, and at high frequencies had very good protective qualities; but at very low frequencies their spark potentials were greater than at high frequency. Other arresters equally sensitive to both high and low frequencies have been installed in the same locality. This experience has indicated that many of the strokes are of low frequency. The most valuable and practical investigation of lightning arresters that has yet been made on a large scale has been carried on by Mr. D. W. Roper, and no doubt these results, which are incomplete at the present time, will be made available at some later date. More direct measurements of lightning taken with an oscillograph have been made by Mr. L. A. De Blois. These, I believe, are the most valuable direct tests that have been made in many years. I am personally indebted to both Mr. Roper and Mr. De Blois for information on their researches, and I understand that their valuable work will be presented to the Institute at some future meeting.*

In the development of the present standard arresters our knowledge of lightning gave us no alternative but to assume that lightning had all the characteristic qualities of the various surges that could be produced in the laboratory. For example, we have assumed:

That the frequency might be from zero to 5,000,000 cycles per second.

*See paper by L. A. DeBlois, *Some Investigations on Lightning Protection for Buildings*, page 519, this volume.

That the wave front might be either vertical or angular.

That the quantity of electricity was both large and small.

We have known from our earliest investigations that several strokes came in succession. It was also necessary to take into account the effects of the energy from the generator which followed the lightning discharges. In this way we have endeavored to be prepared to meet any new information that might come concerning lightning strokes. Naturally, all these different factors could not be given equal weight in the design, and therefore, as more definite information regarding the nature of lightning is obtained, the designs will be strengthened in the features that these investigations may show are weak. It is a matter of increasing the ultimate efficiency by a small percentage.

The direct-current aluminum arrester is practically ideal from the standpoint of protection. It has no series gap and therefrom it gains two valuable characteristics: the first of these is the elimination of any dielectric spark lag; and the second is the absorption of high frequencies which have a less potential than the circuit potential. Commenting on these two conditions, the dielectric spark lag, although it is ever so small, is still appreciable as compared with the time of movement of a surge along overhead lines. A surge will travel a mile (1.6093 km.) in about five millionths of a second. If the surge is a mile long, and the dielectric spark lag is five millionths of a second, such a surge will have passed along the line without starting a spark across the gap. The only means of discharging such a surge would be by introducing a choke coil in its path and thus delaying its movement sufficiently to allow the spark gap to become ionized. Since the spark gap of the a-c. aluminum arrester has a setting which may be only 25 per cent above the line potential, high-frequency surges can be deflected into the arresters if the potential either of the surge or the superposed value on the 60-cycle potential reaches the spark value. If the generated potential happens to be zero at the instant, it is evident that the surge itself must have a value 25 per cent above normal in order to cause the arrester gap to spark. The d-c. aluminum arrester, by its direct connection, is able to pick up surges of all frequencies and all potentials immediately on their arrival at the terminals of the arrester.

The practical demonstration of the protection afforded by these d-c. aluminum arresters confirms the theoretical work and experimental tests made on the cells. The discharge rate at

double potential is more than a million times as great as the leakage current at normal potential.

From a practical standpoint, the cost of such arresters must be considered. While the cost and upkeep of the d-c. aluminum arrester is greater than for the older types using gaps and series resistances, still the aluminum arrester is the more economical one to use. The higher protection given by the cells would justify some increase in expense on account of the better service that can be maintained. But, as a matter of fact, the actual expenditure for the protection as a whole becomes less, due to the fact that good protection on the cars makes a less demand for the use of arresters along the trolley line. The saving in the cost of line arresters will more than compensate for the extra cost and upkeep of the aluminum arrester. Moreover, even with the very best types of gap arresters on trolley cars and trolley lines it is impossible in lightning-infested districts to maintain the car service. The percentage of protection from the gap type of arresters is not high enough even when the best arrangement of wiring and choke coils is used in conjunction with the arresters.

There is one further function of the d-c. aluminum arrester that has considerable value, and that is the absorption of electromagnetic surges coming from the interruption of accidental short circuits on the trolley line. Such high potential across loaded motors has a tendency to cause flashing around the commutators. If the flashing around the commutator is caused by the excess potential, then the d-c. aluminum arrester will relieve the trouble.

Answering, then, the frequently asked question—Will the d-c. aluminum arrester be superseded?—the answer is, in principle, no. Improvement in details may be made, and there may be discovered some new and better substance than the aluminum film, but none is yet known. Any degree of protection that is desired at its terminals can be obtained by the use of this arrester. An improvement in the length of life of the arrester is desirable, but this will not be superseding it. The discovery of some new substance that will give the same electric valve effect at a definite voltage only slightly above the operating voltage would be no particular improvement, unless perhaps it might be something that would not deteriorate when left disconnected from the circuit.

Turning next to the a-c. aluminum arrester, it was found impracticable to maintain simplicity and long life in the arrester

and at the same time keep the arrester directly connected to the circuits. For this reason the horn gap was introduced in series with the aluminum cells. Since the hydroxide films on the aluminum plates gradually dissolve in the electrolyte it becomes necessary to introduce a method of charging the cells. The simplest method was first tried: it consisted of bringing the horns near each other and reducing the gap to a very small value. Many trial installations were made under these conditions and no bad effects were obtained. When the number of arresters in use ran up into the thousands, then an occasional trouble resulted from the rush of current into the aluminum cells.

The aluminum cells are condensers and as such will take initially a considerable rush of current. Furthermore, the dissolution of the aluminum films required a considerable quantity of electricity from the line to reform them. Where the films had been subjected to unusual dissolutions either by standing in hot electrolyte, resulting from atmospheric temperature or long periods of discharging, or from neglect to charge, the current rush into the aluminum cells became a serious menace, mostly to the arrester itself. Since there is no external indication of a bad condition of the aluminum cells, even an expert would be unable to know if it were permissible to close the charging gap of the arresters. This led naturally to the use of charging resistances in series during the ten seconds a day needed to charge the arrester. The charging resistance is an added expense and an added complication. But the added complication is relatively small, and the all-around increase in the safety of the arrester is great enough to justify both the cost and complication, from the user's standpoint.

The subject of possible surges accompanying the charging of aluminum arresters is one far more pertinent in an article written for foreign readers than in one for American engineers. The foreign operators seem to have had misfortunes with their arresters that have not been duplicated in America. The reason for this might be attributed to a number of different causes, depending upon the country and the localities. These reasons might be enumerated as methods and care in manufacture, the lack of definite and emphatic instructions to operators, poor distribution of insulation in transformer coils, and difficult situations caused by any one of several factors, such as, for example,—high temperature, bad regulation of the line, and insufficient care after an arrester had been called on to discharge continuously during an accidental ground.

The general results from any one or more of the foregoing enumerated factors may be classified under two heads: first, a short circuit in the arrester and consequent interruption on the line; and second, surges set up on the line without any damage to the arrester. Nearly all these conditions can be rendered harmless by the use of charging resistances. The one important exception is the matter of bad regulation of a line in which the power voltage is allowed to rise to values above the spark potential of the arrester. Under these conditions of discharge the arrester is no longer being used as such, but rather as a rheostat to absorb the generated power. The arresters cannot, at any reasonable expense, be designed to act as rheostats. While it might, in special cases, be possible to develop arresters which would withstand these conditions, the better solution of the problem is to improve the regulation. If care in manufacturing the aluminum plates and the electrolyte is not taken, and the installation made free of dirt and impurities in the electrolyte, more or less deteriorated conditions will exist throughout the life of the arrester. Certain kinds of impurities have a strong destructive effect on the films. A condition of unusually high operating temperature may call for an electrolyte especially adapted to high temperatures, or it may simply be taken care of by charging two or more times a day. Dissolution of the film from standing in hot electrolyte after the arrester has discharged continuously for a number of minutes can cause no trouble if a reasonable charging resistance is used, as the series resistance limits the current to a value which will not damage the arrester. With the exception, then, of high generator potentials from bad regulation of voltage, there is no difficult problem connected with the use of aluminum arresters.

A discussion of the aluminum arresters would not be complete without some reference to the possible surges that may be set up by the charging of the arrester. Surges on an electrical system may be considered in a list of ascending degrees of severity. Turning on an incandescent lamp sets up an electric wave on the system by calling on the generator for more power. A surge of this kind is of the third order of importance, and therefore, entirely negligible. It is well known that any spark or arc in the circuit containing inductance and capacity tends to set up oscillations, but if the resistance in series is equal to, or greater than, the critical resistance, oscillations will be prevented.

It is common practise to-day to open and close circuits which

contain inductance and capacity without introducing in series a resistance to absorb the transient surges that are thereby set up. It is also common practise to-day to use circuit breakers to open accidental short circuits in which there is a high value of surge energy, and sometimes high voltages.

Going still a step further, every circuit is subject to accidental arcing grounds, which produce continually on the circuit dangerous surges which are often but slightly damped. It is difficult to protect apparatus from these most severe conditions of surges. In general, however, apparatus is built to withstand severe treatment, and there is but a small percentage of loss. Therefore, when we come to consider surges on the system we should take into account the conditions of insulation in relation to the severity of the surge.

In all these graded degrees of severity of surges, where should the aluminum arrester be placed? If there were a demand for it, the arrester could be placed in the list next to the negligible surge of connecting an incandescent lamp to the circuit, and this could be accomplished by using graded resistance in charging. In view of the insulation of the apparatus that is needed for the usual condition of operation and to withstand the inevitable accidents which cause severe surges from time to time, the use of graded charging resistance would be a needless and inconsistent precaution. It is sufficient to say that it could be done if it were desired.

What is actually done is more reasonable. A relatively large value of resistance is used in the charging circuit, limiting the current to a range of 5 to 15 amperes. Charging resistances are an intrinsic part of aluminum arresters as now manufactured. Strong recommendations have been made to operators to add them to their older arresters. A characteristic answer is to the effect that "our arresters have been charged through a gap for six years without trouble, and we are satisfied." The change is brought about not by reason of surges, unless they cause telephone interference, but rather on the ground that the arrester is made more immune from damage to itself.

In foreign countries, with their water jets and resistance types of arresters, the controversy over arresters still waxes as warm as it did here in the formative period some eight or ten years ago. The following argument is advanced against the aluminum arresters: admitting that the charging resistance does away with the surges, what about the heavy strokes which cannot pass

through the charging resistance and therefore jump the main gap directly into the cells to ground? To anyone familiar with the practise here up to 1913 an answer is unnecessary. If this discharge path were a menace, devices could be used to mitigate it. The nature of the menace can be understood by a review of the past practise. There are several thousand aluminum arresters in use that have been charged through a gap without series resistance. Good practise now condemns the method, but there it is. Ten seconds' charge a day produces over a thousand makes and breaks. There would therefore be more than a million total made per day and more than a billion in a few years. Judging by the rare cases of trouble in this vast number it cannot be much of a risk to allow a few discharges per year to pass directly to ground through the aluminum cells, especially in face of the fact that such a surge is so dangerously large that it cannot be relieved through the resistance, and therefore the surge itself is an undoubted menace to the insulation as it runs wild over the electrical system at 186,000 miles per second.

The status of the aluminum arrester, therefore, is that of a device founded on the solid principle of a safety valve. It has definite limits of maximum current discharge rate and of energy absorption, beyond which damage to the arrester will result. In this respect it is no different from other standard apparatus. Years of experience have demonstrated that these limits are far above the usual demands of practise, but naturally it is not impossible to pass them. The flexibility to meet special conditions is great. Film area, internal resistance, relative gap settings, external resistance—all are readily adjustable to the demands which may possibly come as our knowledge of lightning and other surge phenomena is increased.

DISCUSSION ON "THE PRESENT STATUS OF ALUMINUM-CELL LIGHTNING ARRESTERS" (CREIGHTON), NEW YORK, FEBRUARY 27, 1914.

V. Karapetoff: I would like to ask Dr. Creighton whether he has had any experience with the glass condensers and valves made in Switzerland and known there as the Moscicki condensers and Giles valves.

F. W. Peek, Jr.: It is some time since I have been actively connected with work on the aluminum lightning arrester. A number of years ago I had the good fortune to be able to make a study of lightning and the operation of the aluminum arrester on a practical line in Colorado. We had the co-operation of one of the operating companies in the experiments on this system, which was high up in the mountains. It was a 17,000-volt network and a 50,000-volt main transmission, with a 50,000-volt idle line upon which to experiment. Various forms of lightning arresters had been tried by this company without success. It was practically impossible to continue operation during a storm. At this time the aluminum arrester was very new and we did not intend to make use of it as a practical protection; our idea was to make a study of lightning itself. However, in an attempt to improve operating conditions it was decided to install a few aluminum arresters. These arresters could not be obtained from the factory at that time. It was a very difficult country to get into. A sufficient number of aluminum cones was obtained, however; containing tanks were built in the mountains, and the electrolyte was compounded from chemicals bought at a local drug store. An arrester was thus built up and put into operation, and it did very good service. It was decided to install a few more. At a later period in the season these were obtained from the factory and were distributed to various substations. During the latter part of that season there were very severe storms and very little trouble. Many improvements have since been made in the arrester, notably in the electrolyte and in the addition of charging resistance.

The aluminum arrester is the only arrester at present that can take care of a condition of high-energy lightning discharges of moderately steep wave front or moderate frequency. This is often the only condition; generally the prevailing one that must be met. Good protection is thus obtained in the majority of cases, with an occasional miss during the season. There are certain conditions, generally in the minority, but which occasionally on a few systems are the prevailing ones, which no arrester with a gap can, unaided, satisfactorily take care of. These conditions are:

1. Lightning impulses of exceedingly steep wave front and high voltage.
2. Impressed high frequency of a voltage insufficient to discharge the gap.

In condition (1), the dielectric breakdown time lag of the gap may prevent discharge of the arrester before discharge takes place at some weak point in the system.

In condition (2), discharge does not take place at the gap because the voltage is not high enough, but the oscillations may build up high voltage internally in an apparatus containing inductance and capacity.

Both conditions (1) and (2)—which may be considered as more or less special—may be taken care of by the proper arrangement of resistance, inductance and capacity.

Good engineering requires as high system insulation as is economically possible, with the weak point at the lightning arrester.

L. C. Nicholson: Electrolytic lightning arresters are coming to be very widely used, and I think by this time they are recognized as the standard type of station arrester.

Frequently the question is asked—Are they efficient? Are they necessary? We operating people reply by saying, "Yes, they are necessary, if you think so," the result being that most of us are afraid to leave them off. As far as I am acquainted with the operating results of this type of arrester, there is seldom any apparatus damaged when protected by such an arrester, and I will also say that when the apparatus is not protected by such an arrester, there is very seldom any damage. So it appears that the arrester is all right. Except on extremely highly insulated transmission lines, damage to high-tension apparatus in the station by lightning is rare.

Usually lightning effects are so localized that the line has its own trouble and keeps it. I am acquainted with an installation which uses a pretty wide gap between the line conductor and earth, say 100 per cent over voltage, which discharges once a year, and which seems to be about all the protection that the station apparatus really needs, judging from the fact that no station apparatus has been punctured. I am acquainted with other stations which have electrolytic lightning arresters and which are not troubled by lightning and I am acquainted with some which have electrolytic lightning arresters and are troubled by lightning, so that it is very much of a question as to whether lightning will or will not do damage under certain conditions of station protection.

At least, the aluminum electrolytic lightning arresters have been developed to a point where there is no longer any danger of their exploding or giving any trouble on their own account if properly cared for, and the usual station attendant, with sufficient instructions, can properly care for the arresters and keep them in proper service. I feel sure that the addition of charging resistance has been of great benefit to the operation of this arrester.

The pity is that these arresters cannot extend their influence beyond half a mile from the station. In most cases the trouble is beyond that point.

C. O. Mailloux: Reference has been made to the character of the "front" of the wave which strikes a line or a portion of circuit protected by lightning arresters. It is known that the vertical front of a wave may be flattened out and sharpened to a point, so to speak, in passing through a reactance. It would seem therefore, as if one might expect that the character of the wave-front would depend somewhat upon the distance from the apparatus at which the lightning strikes the line. One might expect that the lightning striking the line very close to the lightning arresters would produce a current-wave having a squarer, straighter front, a more vertical one, than if it struck at some distance, owing to the difference in line-reactance. It may be that in most cases this would not make much difference. In any case, it should be possible to alter the wave-front, to some extent, by the introduction of artificial reactance.

C. P. Steinmetz: I wish to refer to only a few features. Setting aside failures of insulation due to weakness or poor design of bushings, insulators, etc., it occasionally happens that even a good lightning arrester fails to protect coils of transformers. The explanation of this is a feature which I have endeavored to make clear in my paper. These failures mean merely that when we speak of lightning we do not know the nature of the surge, and it is necessary to make such studies as will determine it—why at times the surges cause damage and other times they do not.

The aluminum arrester, with a gap in series, may protect against any surge which reaches the aluminum cells. Any disturbance of a voltage less than that which will jump the gap and thus reach the aluminum cells naturally cannot be absorbed by the aluminum cells. Therefore, if we have a high-frequency oscillation of a voltage sufficiently low not to jump the spark gap and incidentally sufficiently low not to do any damage to the line, such a voltage may not be able to do harm to the insulation from line to ground, but when massing of the surge occurs in a few turns of reactance, such as a single coil of a transformer, it may do very great damage, because, while the apparatus is designed to stand the line voltage, it is not designed to stand half the line voltage across say one-hundredth or one-thirtieth of the circuit. The main trouble due to high frequency comes from the local massing of voltage across the reactance.

In speaking of high frequency we may refer to various different effects, and we also usually mean a thing which is not high frequency at all, is not even oscillation—it is steep wave front. A steep wave front, to some extent, causes the same trouble, namely the same massing of voltage, but in other respects it is very different. Some types of protective devices, like the multi-gap arrester, are very sensitive to high frequency, and will discharge high-frequency surges of voltages much less than the operating voltage, but they are not sensitive to steep wave front and may allow steady voltages of steep wave front to rise far above the circuit voltage without discharging.

Another illustration of this difference is given by the application of a condenser. Where there is very high frequency, a condenser shunted from line to ground may bypass or practically short-circuit the high frequency, but where there is a unidirectional wave the condenser will take a charge and thereafter offers no obstruction to the rise in voltage.

We must realize that electrostatic capacity is not a lightning-protective device—is not by itself a protection. A capacity from line to ground merely is a thing which will charge and store the energy. The storage is transient and the energy in the condenser must be returned to the circuit. Thus the condenser in the line will have no effect at all on steady voltage, or on low frequency. The favorable action the condenser can have is apparently to short-circuit disturbances of relatively high frequency.

Such disturbances, in my opinion, are rare, if they exist at all on transmission lines. For the reason that the capacity of the transmission line is so large, compared with the capacity which can economically be provided for in a condenser, any small condenser which can be shunted across the lines at the station would not be capable of appreciably short-circuiting the surge. Thus the high-voltage and the high-frequency disturbances of such volume and such current as can come in over the line are not cared for by any condenser of practicable size.

It is different when the surge comes from the other direction—that is, where the high-frequency disturbance comes from the station. In the transformer, as in the line, the circuits have distributed inductance and capacity, but in the transformers the inductance is very much greater, and the capacity very much less than in the line, and therefore the ratio of voltage to current of the disturbance is very much greater. In other words, capacity has an appreciable effect on a traveling wave, when the capacity is shunted around the high-potential windings of the transformer.

The value of capacity in protective devices lies in the fact that it is a barrier against the passage of current at machine frequency without being a barrier to the passage of surge currents which are inherently of high frequency. Under these conditions it is possible to use a resistance of low value in series with the condenser without absorbing any appreciable power at machine frequency. At high frequency, however, the power factor approaches unity and the maximum possible energy of the surges is absorbed. Thus it is seen that it is not the capacity in itself that is protective, as the voltage absorbed by the capacity at high frequency is negligible, but it is the capacity allowing a properly proportioned resistance to give protection by absorbing the energy of the wave.

This is the condition in the aluminum electrolytic cells, where there is a high equivalent resistance in series with the natural capacity of the cells.

The capacity of the aluminum cell gives a moderate power

factor at average machine frequency, but when there is applied a frequency of 100,000 cycles, the power factor of the aluminum cell is practically unity, that is to say, practically all the high-frequency current which goes through the cell is dissipated as energy and does not store itself as energy to be turned back into the circuit, as would be done by a simple capacity.

I believe that the action of the aluminum cell can best be represented by calling it a counter-electromotive-force device. It acts as a counter-electromotive-force shunt between circuit and ground after the voltage has reached a definite value. Up to this definite value, *i. e.*, discharge voltage of the spark gap, it is an open circuit, and beyond that voltage it is a closed circuit. In the closed circuit condition it has about the same effect as if in a d-c. system you shunt a storage battery from the trolley wire to the ground. If you connect between the trolley wire and ground a 600-volt storage battery, then no lightning or any other disturbance will be able to raise the voltage of that trolley line appreciably above 600 volts, because any attempt to raise the voltage would merely cause a discharge through the storage battery. The discharge rate depends on the internal resistance and voltage above the polarization of the storage battery; so it is in the aluminum cell, where the discharge rate depends on the voltage in excess of the polarization value and on the internal resistance of the cell, which, as we all know, is very low.

Now, as to the possible danger from the use of the aluminum cell, which has been especially discussed by those who have had very little practical experience with it—that is, the question whether it may produce high-frequency oscillation. One argument against the production of high frequency I have mentioned already: the power factor of the aluminum cell is unity and it has no capacity effect at high frequency, but it gives a thoroughly damped circuit of a resistance which prevents oscillations. But from another view-point, the best comparison is that given by Professor Creighton—it is a safety valve from line to ground, of very high discharge rate.

We would not think of installing a high-pressure steam boiler without a safety valve, and still, many of us know that every once in a while you hear that a safety valve is really a source of danger, because if a steam boiler is superheated, and water is low, and just at the point where it is near blowing up, and if the safety valve operates, then the sudden shock of the safety valve opening may set off the explosion. But that is no reason for saying that it is unsafe to use safety valves and that all the steam boilers should be operated without them. It is exactly the same case with the aluminum cell or any protective device. If you protect the system against over-voltage, and if the energy back of the over-voltage is very large, it means that to relieve the over-voltage strain we have to provide a device with a high discharge rate, and the sudden coming into play of that high discharge rate, which is required to relieve the strain, means a sudden

shock to the system, and if you are near the breakdown point, that very shock may cause a breakdown.

But it has been said that it is not necessary to have a free discharge, and that a resistance may be inserted between line and ground—a critical discharge resistance which will gradually relieve the voltage without oscillations. That is very nice. By so doing the shock is removed only by keeping the excess voltage on the line and the apparatus for a considerable time, and for the time, in fact, that it takes to discharge, and since the disruptive strength depends on the time of applied voltage we wish to relieve, we must conclude that we are between two extremes. We have a condition of excessive voltage brought on by lightning or other disturbances. This voltage is dangerous, is certain to destroy apparatus and line if it stays long enough. We may gradually relieve, or we may suddenly relieve, but since the voltage is certain to destroy, the most effective way is to relieve it as quickly as we can, even if in the extreme case the very suddenness of the relief may accelerate the damage, which is, however, very improbable. I do not know of any instance where this has occurred, and I think the point raised in this connection is more theoretical than actual.

There is one point I want to mention about steepness of wave front. The steepness of wave front depends on the distance of the place from the point where the wave originates. Theoretically, if you calculate transient phenomena of the line, you will find, by an equation, that the wave shape is so steady that the wave starting as a steep wave front retains its steep front all over the line. Practical experience shows that this is not so, and that is one of the various points where theory and calculation do not agree, or where, in our theory, we make an assumption which we find is not warranted—that is, we assume the effective resistance and effective conductance to be constant, independent of the frequency, while in reality every decrement increases with increase in frequency.

If you assume that the effective resistance of the line is a function of the frequency, increasing with increasing frequency, then you would find in the equations (if the equation did not come out so complicated) which so far have been beyond the mathematical skill brought to bear upon them, that the steepness of the wave form decreases with increasing distance traveled by the wave.

But while the equations have not yet been solved to give the values of the increase in resistance of the line, experimental evidence is available. There were some very interesting tests, for instance, made by Mr. Faccioli some years ago, on the wave produced by opening the high-tension switch in a 90,000-volt circuit. In that case, at and near the point of opening of the switch, the steepness of the wave front was such as to give, across a choke coil the inductance of which was equivalent to 50 feet of line, a potential difference of 30,000 volts, but the same size of coil on the same line at 20 miles distance,

gave no appreciable steepness of wave—that is to say, in the switching test there was no discharge on the spark-gap shunted around this small reactance. Within 20 miles of travel the wave front changed from an extremely steep one to a very flat one. This is the experimental evidence of the high resistance offered by the copper line wire when the potential is suddenly applied.

E. E. F. Creighton: I feel that there is no need to say anything further about the Moscicki condenser, in answer to Dr. Karapetoff's question, as Dr. Steinmetz has already covered the subject.

I am glad that Mr. Nicholson has thrown a little spice into the controversy by speaking of the cases where apparatus was not damaged and the arresters were installed, and also cases where the apparatus was not damaged and the arresters were not installed. Each one of us speaks from his experience, especially his own personal experience, and Mr. Nicholson, I take it, is speaking from his. If I may be permitted, I would like to analyze some of the conditions under which he has been operating and then contrast them with some other experiences which have been gained on other transmission lines where the conditions are different.

On that particular system to which Mr. Nicholson referred there was, a few years ago, an almost insurmountable problem of keeping the lines operating during thunderstorms. I have the greatest admiration for the way in which Mr. Nicholson has attacked this problem and obtained a workable solution. The point of it was that the insulators on the line had not only less factor of safety than they needed, but they punctured, and where every insulator on the line is a lightning arrester it is quite true there is less need of lightning arresters in the station. Under these conditions the principal need of a lightning arrester in the station is where the lightning happens to strike in the neighborhood, and that, I think, corresponds to Mr. Nicholson's remark that it is too bad the lightning arresters cannot reach out more than a half-mile from the station. I should say that it is too bad the lightning is so terribly concentrated at points on the line. That represents, to my mind, the experience gained in that particular case.

On two other lines I know of, where the insulation of the lines was made for operation at 100,000 volts and the operating voltage was only 20,000 and 40,000 volts, the results were quite different. Since the factor of safety of the insulators was about 10, they were not functioning as lightning arresters or protectors for the apparatus, and consequently every lightning stroke that appeared on the line came with horrible impetus into the station. Switch bushings, transformer bushings, and other insulation that had withstood the conditions of other circuits, immediately began to break down from flash-over or by puncture. Lightning arresters of the best type were then required.

This is a condition that is gradually growing all over the country. Everywhere operators find that insulation on the line is an important factor, and are increasing the factor of safety in the line insulators. Personally, I would never use a factor less than three times normal potential, preferably still higher. The extra investment in insulators is worth while. This ultimately necessary practise will increase the need of lightning arresters.

The lightning arrester in itself is not a surge protector, but an over-potential protector. The gap setting is 25 per cent above normal operating voltage, and the arrester will operate as a surge protector only after the gap sparks and connects the aluminum cells directly to the line. I am somewhat disappointed that there has not been more adverse criticism, as our foreign friends are finding a great many things to say. I feel that any criticism or any failure of the aluminum arrester to protect the circuit can be explained by some weak local condition, or, otherwise, the design of the arrester can be easily modified to meet new conditions. As Dr. Steinmetz has so well emphasized today, the great need at the present time is more definite information. A few years ago it was a very common thing to have bushings fail on transformers and switches, but today, due to the presence of the aluminum lightning arrester, these faults have almost entirely disappeared. Those that have not disappeared I hope to be able to give a reason for, at some not far distant time, as a result of the study of porcelain insulators at high frequencies. Porcelain insulators and bushings have a different strength at 60 cycles on which they are usually tested, from their strength at very high frequencies, such as 200,000 cycles per second—or its equivalent, expressed as steepness of wave front.

Presented at the 292d Meeting of the American Institute of Electrical Engineers, New York, March 13, 1914, under the auspices of the Telegraphy and Telephony Committee.

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TRAFFIC STUDIES IN AUTOMATIC-SWITCHBOARD TELEPHONE SYSTEMS

BY W. LEE CAMPBELL

ABSTRACT OF PAPER

The paper describes a telephone traffic recording machine by means of which not only the number of calls for a given period, but also the average duration of each call, is mechanically registered on a moving tape. The observations recorded here were taken on an automatic telephone system. The graphical record shows the exact duration of each connection, the number of connections made during a given interval, and the number of simultaneous connections in service at each instant. By means of these records it is possible to study the relative efficiency of small and large trunk groups, the average holding time of calls, and these observations permit the switches and trunks to be so arranged that the calls will be evenly distributed among the trunks in each group.

THE WORD "traffic" as used in telephone practise applies to the volume of calls which a system handles. To measure traffic it is necessary to know not only the number of calls for a given period or interval of time, but also the average duration of each connection or call. A knowledge of traffic, and the laws governing it, is essential to the proper design and operation of either an automatic or a manual system.

OBSERVATIONS OF TRAFFIC

In well-managed manual switchboard central offices it is customary to study traffic conditions by taking peg counts and plug counts. A peg count is a count of all connections made during a definite time interval by each of the operators. A plug count is a count at a definite instant of all plugs in use. In addition to these, stop-watch observations must be made to determine the average length of connection, or "trunk holding time", as it is often called. Where the trunk holding time is known, a good way to take both a peg count and a plug count has been to use a recording ammeter connected into a circuit supplying energy to some or all of the relays; then knowing the average ampere-hours consumed by each connection, it is a

comparatively simple matter to determine from the ammeter records both the total number of connections made and the maximum number of connections existing at the busiest instant. The latter is an especially important matter because it determines the amount of connecting equipment required to take care of the peak load.

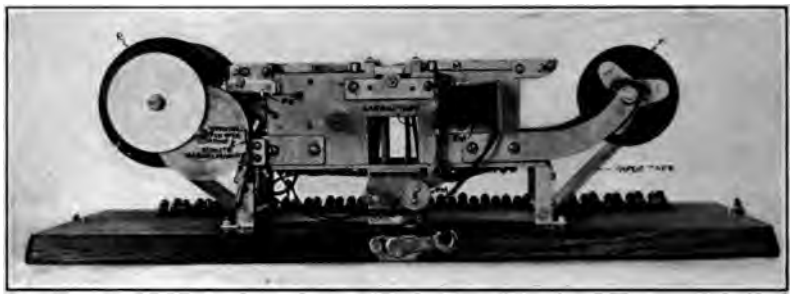
It is very difficult, if not impossible, to secure a very accurate peg count or plug count. Operators frequently make mistakes in registering calls during a peg count and observers make mistakes in counting plugs; mistakes are also made in distinguishing between cord circuits actually in use and those which are apparently in service but really idle, because the conversation of the parties using them has been completed.

In automatic central offices, counts corresponding to peg counts are occasionally taken by counting the operating switches as they complete connections. Calls are also counted by the use of a meter on each trunk; these are generally installed by connecting the release magnets of 2nd or 3rd selector switches on each section of the switchboard to a separate busbar, in series with which is a ½-ohm relay which operates each time a switch releases, and closes a circuit through a meter. Counts similar to plug counts have been taken by counting all of the like trunking switches in operated position at given times.

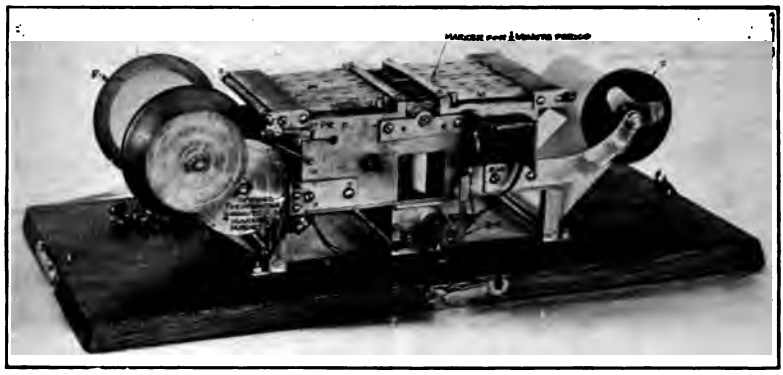
Traffic-Recording Machine

All of these methods of measuring traffic have their disadvantages and it is believed, therefore, that telephone traffic engineers and telephone engineers in general will be interested in a new recording device and some of the results secured by its use during the past year in making traffic studies in automatic switchboard plants, on a somewhat elaborate scale. The special feature aimed at in this machine was to secure a graphical record which would show the exact duration of each connection, the number of connections made during a given interval and the number of bona-fide simultaneous connections in service at each instant.

The machine as devised consists of a mechanism for passing a strip of paper about 6 in. (15.2 cm.) wide over an inked ribbon and onto a receiving roll at definite rate of speed, with a number of markers (40 in all) arranged side by side over the paper, so that when any marker is pressed against the paper the inked ribbon leaves a corresponding line on the paper. Each marker



[CAMPBELL]



[CAMPBELL]

FIG. 1

is provided with an armature and an electromagnet for operating it; the latter is electrically connected to the mechanism associated with one automatic switchboard trunk in such a way that whenever that trunk is occupied by a call, the potential established on the trunk for guarding purposes serves also to cause current to flow through the electromagnet and energize it as long as the connection lasts.

Two views of this machine are shown in Fig. 1. *F* is the roll feeding paper to the machine; *R* is the receiving roll; *M* are the markers; *V* is a pendulum vibrator tuned to run at a fixed speed, so as to make and break at regular intervals the circuit through the electromagnet operating the step-by-step pawl and ratchet movement *PR*, which turns the receiving roll and thus draws the paper through the machine; *R M* is a device for moving the ribbon at intervals so that the portion immediately under the markers will always be sufficiently inked. A skeleton view of the mechanism with its associated circuits is shown in Fig. 2.

Sample Observations with Machine

A section of the paper tape taken from the machine and covering a record of calls during a busy half-hour on a set of trunks in the business central office of a city in Michigan is shown in Fig. 3.

One especially interesting feature is the remarkably short period of time which occurred in many instances between the release of a trunk and its seizure for another connection. This is of material aid in promoting trunk efficiency, and is due to the automatic switchboard. As indicated in the figure, the vertical lines mark $\frac{1}{4}$-min. periods. It was found that by means of a chartometer, it was not a difficult matter to sum up the lengths of the lines on each tape, so that the average length of call might be obtained; and it is apparent that a curve may be very readily made from this sheet, which will show the number of simultaneous connections at each instant, as the curves in Fig. 4. In fact, any traffic data desired may be secured from the tape.

The upper curves *A* and *B*, in Fig. 4, are taken respectively from the upper and lower halves of the same tape, from whose totals the lower curve was constructed.

Trunk Efficiency

The writer's purpose in presenting these curves is to give a graphical illustration of the relative efficiency of small and large

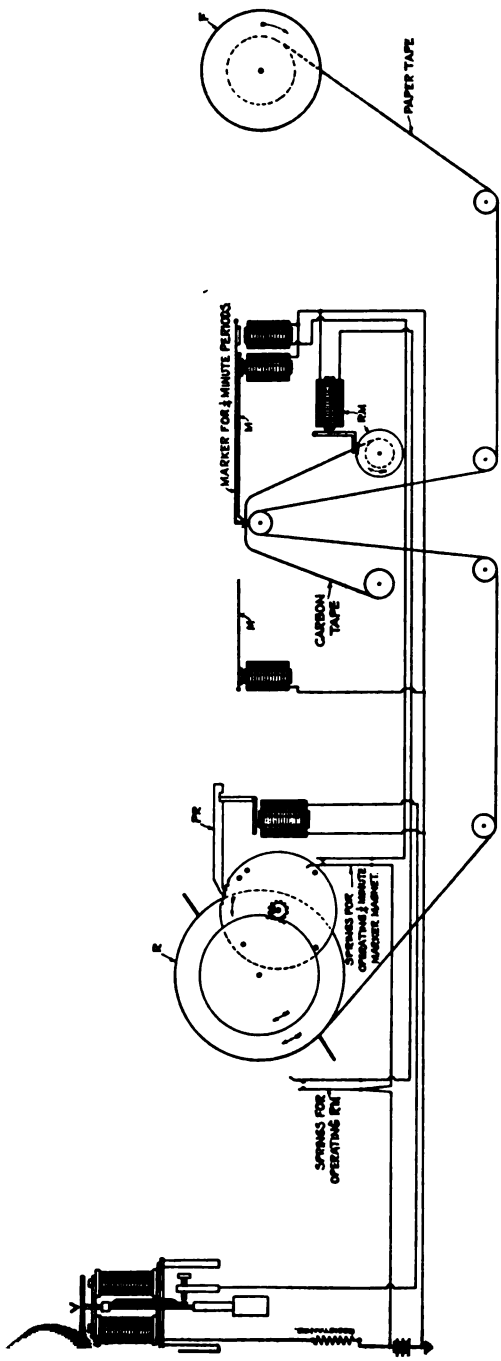
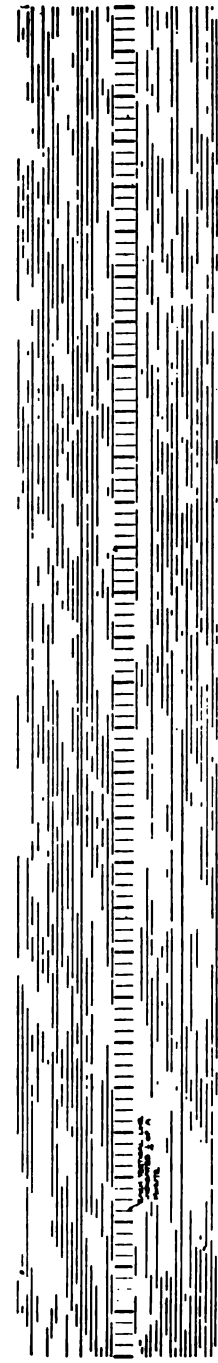


FIG. 2



SECTION FROM TAPE OF TRAFFIC RECORDING MACHINE.

FIG. 3

trunk groups, by noting the fact that while in the group *A* the maximum number of simultaneous connections is 18 and in group *B* the maximum number is 18, the maximum number in a combination of the two is not 18 plus 18, but 32. This is merely an illustration of the law of increase in efficiency of trunks as the size of the group increases which has been well known to telephone engineers for years; but the author is not aware of any other device which makes it possible to study the working of the law so satisfactorily. The fact that the greater efficiency of large trunk groups is due to a smaller ratio of peak load to average load is very clearly demonstrated by the curves

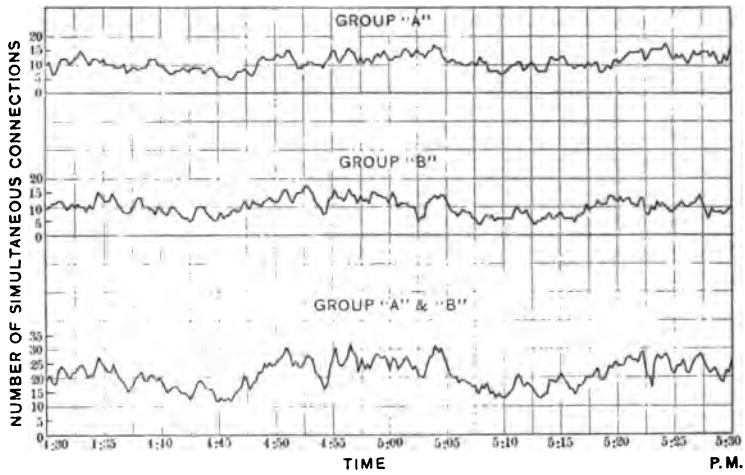


FIG. 4

in Fig. 5, which were constructed from data secured in an office of 7950 lines, by making simultaneous observations during the busy period of each of six working days, on the number of connections in service at given instants in each 100-line section of the entire plant. Note the much greater variation (Fig. 5) in the percentage of connections in the average 100-line group than in the 1000-line section, and the very small variation in the load of the entire plant.

It is customary to define the peak load in terms of the average load or the total busy-hour load. One of the curves, *A* in Fig. 6, shows, for calls of 83 seconds duration, the relation between the total busy-hour load and the peak load, in automatic

switchboards; or, in other words, the number of trunks needed at the peak instant for busy-hour loads of various sizes. This curve follows the formula:

$$\text{Number of trunks} = T\ C + 3.785\ (1-T)\ \sqrt[3]{C\,T} \qquad (1)$$

For call lengths of less than 130 sec. this formula may be written in the simplified form:

$$\text{Number of trunks} = T\ C + 3.7\ \sqrt[3]{T\ C} \qquad (2)$$

T is the average holding time in hours, and C is the number of busy-hour calls.

Average Holding Time

The curve B in Figure 6 is drawn for an average holding time of 83 seconds, because some tens of thousands of obser-

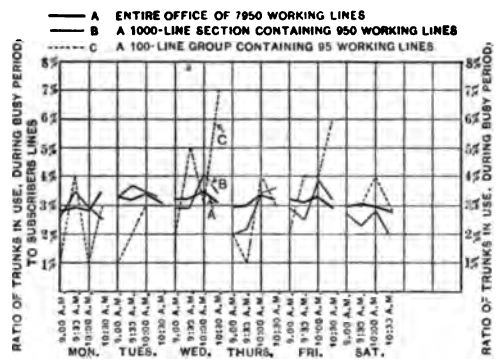


FIG. 5

vations made in different automatic plants show this to be slightly above the average duration of connection. The 83-sec. standard is divided as follows:

Setting up of automatic connection.	6	sec.
Waiting for called party to respond..	9.5	"
Conversation.....	66.5	"
Release of connection.....	1	"
Total.....	83	sec.

Call lengths vary greatly in different offices. For example, in one of the cities in which studies were made with the traffic recording machine, it was found that while the average length of calls for the entire system was 81.25 sec., it was 130 sec. on the trunks to an outlying residence office and 100 sec. on trunks to

manual private-branch exchanges; but observations made on inter-communicating calls in automatic private-branch exchanges have, in a number of instances, shown an average call length as low as 43 sec.

In connection with the studies of average call length, it was found that in approximately 12 per cent of the calls the calling party received the busy signal; and 16 per cent received no response from the called party, either because he was beyond the reach of the telephone, or did not answer the signal before the calling party disconnected.

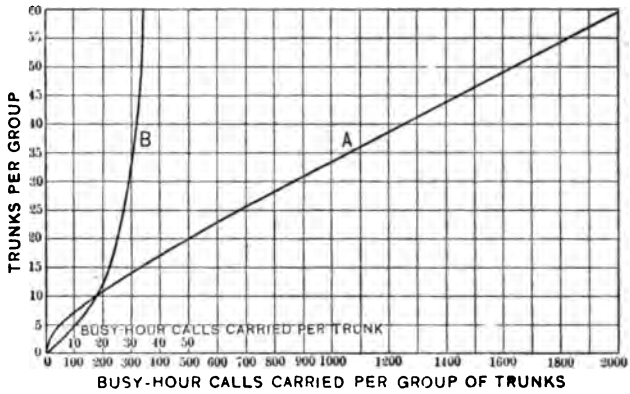


FIG. 6

Curve *A* shows relation between the number of busy-hour calls and circuits in a group. Average holding time 83 sec. Automatic system.

Curve *B* shows the relation between the number of circuits in a group and the number of busy-hour calls carried per circuit.

TRUNK GROUPING

It is common practise in automatic switchboard systems to arrange the switches and the trunks so that the calls will be evenly distributed among the trunks in each group. This is done to distribute the wear on the trunking switches, to ensure all the switches enough operation to keep them in good working order and to reduce the risk of two parties seizing a trunk at the same instant. Sometimes it is advisable, however, to provide that the trunks in a group will be selected successively: for example, if there are 10 trunks in a group, the trunk-selecting mechanism will test the trunks in order, starting at No.1 for each call, and seize the first trunk that is disengaged.

In Fig. 6A are given some curves showing results of observations made with the traffic-recording machine on groups of

trunks successively selected. The shape of these curves gave rise to the suggestion that two groups of 10 trunks each, for example, might be reduced without loss to two individual groups of 7 trunks each and a common group of 3 trunks, which would be a total of 17 trunks instead of 20, by connecting in multiple the 8th, 9th, and 10th trunks of each group after the manner

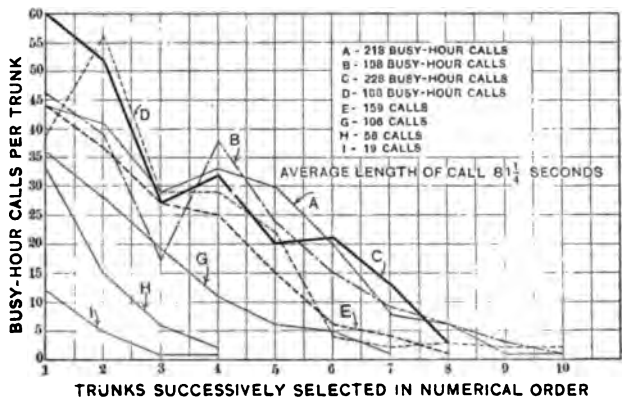


FIG. 6A

shown in Fig. 7. The effect of this method of connecting the groups together is illustrated in Fig. 8, which shows the load curves of the two groups of trunks overlapped in such a way that the one busy-hour call of the 10th trunk in each group is superimposed on the 9 busy-hour calls of the 7th trunk in the other group, while the 3 busy-hour calls of the 9th trunk in one group are combined with those of the same trunk in the other group.

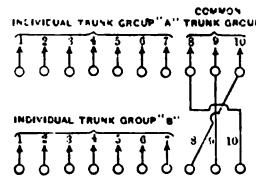


FIG. 7

It is argued by those who suggest this scheme that since, as shown in Fig. 6, a group of subscribers *A* making 175 busy-hour calls would require but 10 trunks and a similar group *B* would require but 10 trunks, while a group of subscribers making 350 busy-hour calls would require but 16 trunks, the arrangement in Fig. 8 satisfies all requirements; because it must be true that the peak loads in the two sets of 10 trunks each would practically never overlap, so that both groups of subscribers would never want the 3 common trunks at the same time, or else the curve in Fig. 6 and the law governing it are fallacious.

There is one other factor to be considered, however, and that is the possibility of calls overhanging on the 3 common trunks, while some of the subscribers of the group A, for example, are not calling, and group B parties are endeavoring to secure access to the common trunks. The arrangement in Fig. 7 and Fig. 8 allows an extra trunk to overcome this objection, *i. e.*, allows

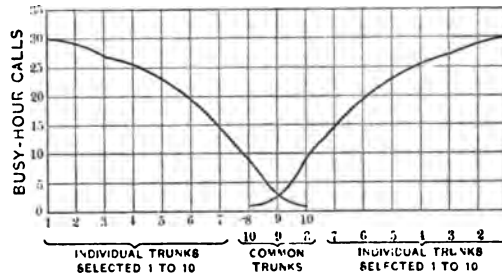


FIG. 8

17 trunks for 350 busy-hour calls, while but 16 would be required if all subscribers had access to every trunk.

Whether this arrangement will be justified by experience and become of practical value, the writer would not venture to say at this time. It seems probable that it could be practised to advantage where two-way trunk service is to be given. As the writer mentioned in a previous paper, there is generally a dif-

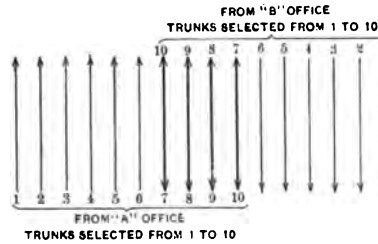


FIG. 9

ference in the times at which the peak loads occur on trunk groups carrying traffic in opposite directions between two offices, consequently the use of two-way trunks would reduce the number of trunks required. While such trunks have not been found feasible between large manual offices, they are nevertheless practical, and some of them are in use in automatic systems.

The obstacle in the way of their more general installation

is the increased cost of trunking equipment. This obstacle can be largely eliminated by the scheme illustrated in Fig. 9, which shows 16 trunks interconnecting two offices *A* and *B*, in such a way that each office has access to six individual one-way trunks and four two-way or common trunks. This plan allows for a peak load in either direction of 175 busy-hour calls, provided the two peaks do not occur at the same time, and the combined group would carry a load of at least 240 calls. It is evident that the number of common trunks might be greater or less than four in a total of 20, and would be determined by the relation between the two-way peak load and the peak of the load in each direction; also that the expensive two-way equipment is confined to the comparatively few two-way trunks.

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A COMPARISON OF THE TELEGRAPH WITH THE TELEPHONE AS A MEANS OF COMMUNICATION IN STEAM RAILROAD OPERATION

BY M. H. CLAPP

ABSTRACT OF PAPER

Brief historical descriptions of the use of the telegraph and the telephone on railroads are given, the first train having been handled by telegraph in 1851 and the first handling of trains by telephone on long stretches of main line track having started as late as 1907.

In comparison with the telegraph, the telephone circuits cost more to install and operate, but effect a saving in the operation of the railroad, both directly and indirectly, as it is possible to move trains over the road more rapidly.

The advantages and disadvantages in comparing the telegraph with the telephone are summarized as follows:

In Favor of the Telephone. Universality, saving of time, rapidity of transmission, psychological effects, promptness in raising offices, no necessity of specially trained operators, saving in expense of railroad operation, and best operation of circuit in heavy weather.

In Favor of the Telegraph. Flexibility in handling circuits, simplicity in installing, maintaining and operating, circuit best adapted for long distances, effects of distance in transmission, saving in cost of installation and maintenance, and the standard of maintenance.

In considering what are termed the four methods of communication, namely: by personal interview, by letter, by telephone or telegraph message, and by telephone conversation, attention is called to the fact that the use of the last-mentioned method by the railroads in this country has not been carried as far as it should.

IN MAKING a comparison between the telegraph and the telephone in their application to railroad operation, it is the purpose to state first the principal physical characteristics of each; secondly, the respective costs of providing and maintaining them, and, finally, the relative advantages and disadvantages of these two means of communication. A brief résumé of the early development will possibly serve to make clearer the situation which so long delayed the advent of the telephone for handling trains.

EARLY DEVELOPMENT

From the beginning of the operation of railroads in the United States in the early 30's, until the early 50's, a period

of twenty years, there was no system provided for rapid communication from one station to another. Trains were run on what was called the "time-interval system;" briefly, a ruling train had the right of one hour against all opposing trains of the same class. This practise continued for nearly ten years after Prof. Morse had sent his historical message from Washington to Baltimore. At about that time the Erie Railroad Co. constructed a telegraph line, which was first used, apparently, for handling local messages along the road. Finally, in 1851, a train was successfully handled by a telegraph order for a distance of 14 miles (22.5 km.) From this small beginning the handling of trains and messages by telegraph increased very rapidly, until, about ten years later, the telegraph was quite common on the railroads of the country. Contracts were early made between the railroads and the commercial telegraph companies whereby the same pole lines were used by both parties to support their wires along railroad rights-of-way. In the end, the telegraph became an established and invaluable adjunct in railroad operation, as will be described in more detail.

Although the Morse register was early done away with, and messages received entirely by sound, there was some opposition to this on account of the loss of the permanent record, especially when dispatching trains. This matter of not having a record was one of the principal reasons that the telephone was not sooner used for the dispatching of trains; but when this objection to the telephone is analyzed, we find that there is really no difference between the receiving of a message by sound on the telegraph as compared with receiving a message on the telephone, as no record is made in either case by the electrical or mechanical equipment proper. Apparently some of the persons who objected to the use of the telephone on account of its alleged lack of record, had in mind, when they considered the telegraph, the old Morse registers that were first used on the early telegraph circuits.

The railroads early began to use the telephone on different parts of their systems. As the commercial development of the telephone was very slow in this country up to 1890, it would apparently follow that there was not very much use of the telephone on the railroads during the same period. However, the records show that different railroads in the early eighties began to put in telephones for various purposes; not

so much, however, to replace the telegraph, as to replace messenger service and to serve as an auxiliary to the telegraph. The replacement of the telegraph by the telephone, to any extent, really began only six or seven years ago. It is only during this short period of time that extensive installations of telephone dispatching and message circuits have taken place, although beginning about fifteen years ago there were numerous telephone circuits erected between terminals and principal offices on some of the railroads. These long-haul talking circuits did not primarily replace the telegraph, but in most cases merely provided additional means for communication.

While trains were handled for short distances, principally in and about terminals, beginning back in the early nineties, it was not until the latter part of 1907 that any real attempt was made to handle trains on long stretches of main-line track by telephone. The Chicago, Burlington and Quincy road was one of the first to use telephone train-dispatching circuits on its main lines, and by the latter part of 1908 this company had a considerable mileage of its lines dispatched by telephone. The principal railroads in the East and the middle West at once began to install telephone circuits, so that at present there are some 70,000 miles (112,654 km.) of railroad in the United States dispatched by telephone. The use of the selective-ringing telephone circuit for the dispatching of trains was soon followed by the use of the same kind of circuit for the handling of messages. The growth of the telephone message circuit has, however, been very much slower than that of the dispatching circuit. The primary reason for this is the fact that the telephone message circuit does not meet the conditions on the average railroad to the same advantage as the dispatching circuit, there being more complications to meet than in the case of the dispatching circuit. In general, the message circuit requires a considerable amount of traffic to justify its use. However, it will only be a question of time when all telephone dispatching circuits are paralleled by telephone message circuits.

A Typical Railroad Telegraph System

The outside and inside plants used by different railroads necessarily vary to a large degree on account of the different sizes, resources, locations and conditions of the railroads served. A description will be given, therefore, of the system on one of the large transcontinental railroads with which the writer is

most familiar, with particular reference to the conditions about seven years ago, when the present extended use of the telephone for dispatching trains and handling messages had its beginning. It will not be necessary to describe in detail the pole lines used to carry the wires, either telegraph or telephone. It will be sufficient to say that these lines in the United States are in a great majority of cases constructed in accordance with the specifications of the Western Union Telegraph Co., which is substantial construction. These pole lines have at least thirty-five poles to the mile, where the number of wires to provide for is considerable, and in some cases 40, 50, 60 and even 70 and 80 poles per mile are used.

At first iron was universally used for telegraph wires, the size most used being No. 8 B.W.G., thoroughly galvanized. This practise, in general, was not changed as far as the railroads were concerned, except that a considerable amount of copper was put up for long-haul circuits. Of course, copper wire is used quite extensively near large centers or along the seacoast, or wherever corrosion would be troublesome. When copper wire is provided, No. 9 A.W.G. is generally used.

The average cost per mile (1.6 km.) for furnishing and erecting a No. 8 B.W.G. iron wire, including insulators, tie wires and pins, is about $25.00. This wire makes a very good telegraph circuit up to 400 miles without any intermediate offices. At this distance the wire can be worked either single, duplex or quadruplex. With intermediate (way) offices on the line the above-mentioned distance would be cut down to about 200 miles (321.8 km.). The matter of line insulation has a very important bearing on the distance that an iron wire or, in fact, any telegraph wire can be successfully operated. The distances given above assume a high grade of insulation. This mileage for the operation of iron wires, however, is ample for almost any division of a railroad, so that iron wire is very generally used in railroad local (way) circuits, copper wire being used between terminals and the principal points along the line. On the Northern Pacific system, when telephone circuits began to be extensively installed, about seven or eight years ago, there were the following mileages of copper and iron wires in use:

Copper,	4,000 miles (6437 km.)
Iron,	11,500 miles (18,507 km.)

There were practically two through copper wires from St. Paul to Tacoma, a distance of a little less than 2000 miles (3281 km.);

all the rest of the circuits on and between the different divisions were iron. At that time this wire plant was considered a very good one for the purpose for which it was intended.

The cost per mile for providing and erecting No. 9 B. & S. gage copper wire, including insulators, pins and tie wires, varies greatly with the price of copper, but assuming fifteen-cent copper, it would be, on the average, about $38.00.

The equipment of a telegraph office is comparatively simple and needs no description. The following costs will be of interest in comparison with the cost of telephone equipment.

A way station can be cut-in on a telegraph wire, including the battery (gravity) in the office, at a total average cost of $12.00

A switchboard (peg type) large enough to take care of ten wires, in and out, can be provided and installed at a cost of $42.00

The cost of providing and installing a twenty-five-line Western Union switchboard, with twenty wires cut in and out, and eight sets of telegraph instruments with necessary tables and battery, is about.... $140.00

Nineteen-conductor cable (No. 14 A.W.G.) suitable for connecting the wires from the line into the offices, can be provided and installed at an average cost of 30 cents per foot.

The average cost of providing and installing a quadruplex set would be about $200.00

The average cost of providing and installing a single-line repeater set would be about $50.00

At terminals, of course, more apparatus is necessary than at the way-stations along the line. However, a cost of $400.00 would provide and install the equipment in almost any terminal or relay office along the line, except the very largest. While the above-mentioned figures are approximate, and are averages for conditions on the transcontinental line with which the writer is most familiar, they are believed to be reasonable and to give some idea of the cost of providing telegraph circuits along a railroad.

Railroad Telegraph Traffic

On a railroad on which the telegraph is the only means for transmitting intelligence quickly from point to point on the system, except for short distances in and around terminals where the telephone is used extensively, telegraph communication is used by all departments and by a large percentage of the employes on all occasions and on all subjects. In fact, it is no exaggeration to say in general, that the sending of telegraph messages is made so easy that a great many more messages and words are sent than necessary. The telegraph office is usually located close to the Superintendent's office at division points, and at General

Headquarters is made as accessible to all departments as possible. In headquarters buildings, where a considerable amount of space and a number of floors are used, pneumatic tube systems are provided in order to carry the messages back and forth between the different offices and the telegraph office.

A considerable amount of railroad business is from its very nature urgent and requires as quick action as possible; for example, reports on the progress of trains over the division, the meeting of the various emergencies that arise, messages about shipments of different kinds, reports of the location of equipment along the road, and similar business.

Each section of railroad has, between terminals, at least one message wire and one dispatcher's wire, unless it is a very unimportant section such as a branch line, where one wire, in a great many cases, serves the purpose for handling both the messages and the dispatching. The length of railroad that can be handled by one telegraph message or dispatching wire depends upon the amount of traffic handled, the size of the towns along the line, kind of country through which the railroad is built, etc. On a busy single-track railroad, 100 miles (160.9 km.) would be a fair limit for telegraph dispatching of trains by the use of one circuit. The facilities necessary for handling the messages would, in a great many cases, be the same as those required for the dispatching, although there would be a great deal more variation in handling the messages than the dispatching. On an important section of railroad there is usually one message circuit that cuts into all offices along the line (way or local circuit) between the two terminals, with other circuits cutting into the more important points.

In order to handle the message service to and from the general headquarters a system of through circuits is provided between the different division points and the general offices. If the length of the railroad system requires it, relay and repeater stations are established. For example, on the Northern Pacific system there are four relay offices between St. Paul, Minn., and Tacoma, Wash. In these offices are located, with a few exceptions, the multiplex telegraph equipments (duplex and quadruplex); there the business is relayed to different offices and terminals to which direct wires are not provided. The wire testing is also handled at these points. On most railroads in the West the operators in the relay offices are on the pay-roll of the Superintendent of Telegraph and are handled directly by him. This

arrangement tends to give uniformity to the telegraph service on the system.

In order to give an idea of the extent of the telegraph system on the Northern Pacific, the following list is submitted, giving the assignment, the character of circuit and the mileage to the destination, of the principal telegraph wires working at the present time out of the St. Paul general office:

Circuit Assignment	Character of Circuit	Distance in Miles
St. Paul-Tacoma, Wash.	Quadruplex	1900
St. Paul-Missoula, Mont.	"	1250
St. Paul-Spokane and Pasco, Wash.	"	1650
St. Paul-Helena, Mont.	"	1130
St. Paul-Billings and Livingston, Mont.	"	1008
St. Paul-Dickinson, N.D., and Glendive, Mont.	"	667
St. Paul-Fargo and Mandan, N. D., local, 35 offices	Quadruplex to Fargo Single to Mandan	450
St. Paul-Fargo, N. D., and Dilworth, Minn.	Quadruplex	252
St. Paul-Duluth, Minn.	Duplex	152
St. Paul-Winnipeg, Man., Local, 32 offices	Single	483
St. Paul-Fargo, N. D., Local, 41 offices	Single	252
St. Paul Division, Local, 30 offices	Single	170
St. Paul-Duluth, Minn., Local, 40 offices	Single	152

This list includes only the principal circuits and does not include certain locals operating out of St. Paul to points in the immediate vicinity of the Twin Cities.

While there is no very accurate record of all the messages handled between all points on the system, the total is estimated at about 5,000,000 per year, not including any messages at present handled by telephone. This would appear to be a large number, even when it is considered that the Northern Pacific is operating over 6000 miles (9656 km.) of mainline track, and it shows, apparently, the free use that is made by this railroad of the telegraph message facilities. According to the writer's observations, the conditions in this respect on other railroads are not materially different.

The cost per message for handling communication by telegraph will probably average more on a railroad than the message cost of the commercial companies, because the messages are handled on the railroad in smaller offices, and on circuits on which the number of offices is larger. The labor cost per message in Northern Pacific relay offices is a trifle over two cents; in offices along the line it would be hard to say what is the actual cost per message, on account of the multifarious duties of the operators at most of these points.

Principal Advantages of the Telegraph

The principal advantages of the telegraph are its simplicity and its small cost, both as regards installation and in maintenance; this statement being made, of course, in comparison with the telephone. There are no very complicated circuits in connection with the telegraph, especially at the great majority of the offices along the line. The ordinary lineman has no difficulty in learning how to install and maintain sets of telegraph instruments, and with a little experience, he is able to install duplex and quadruplex apparatus, and Western Union peg switchboards. In general, no particular care is necessary in running telegraph circuits, with respect to one another, in order to avoid induction either in the offices or on the line. In making the last statement, however, the author fully appreciates that telegraph circuits have been seriously interfered with by induction in certain cases; the conditions in mind are those which exist, as a rule, on the great majority of railroads where the telegraph is used. Also, a telegraph circuit will operate under defective maintenance conditions, such as loose connections, unsoldered joints, defective office and cable-box wiring, high resistances in series with circuit, etc., where a telephone circuit would absolutely fail. In other words, the telegraph circuit usually has a considerable amount of margin in operation and will stand a large amount of neglect and abuse. The cost, as already indicated, is small for both line wires and office equipment, and while copper wire is used to some extent, iron wire serves the purpose in a great many cases where it would not be possible to use it in connection with the telephone. The telegraph, also, has the advantage of being a very accurate means of communication. A telegraph sounder makes very clear and distinct signals, and to an expert operator, there is no question as to what has been transmitted; and, if the wire is working at all, the distance is not much of a factor, because the sounder is in a local circuit.

Disadvantages of the Telegraph

The great disadvantage of the telegraph is its lack of universality. It requires a specialist in order to operate it; that is, an operator who has spent a considerable amount of time, years in some cases, in order to qualify for the work. When carrying on a telegraphic correspondence, one is always working through some one else, never directly. This condition is satisfactory

in handling some kinds of business, but not for all kinds. The train conductor out on the line can, in the case of an accident, send messages by telegraph to his superior if there is a telegraph office near at hand in which operators are on duty, and accomplish certain results; however, if he can talk directly with his superintendent, a great deal more can be accomplished. The same is true of the section foreman out on the line, the superintendent in his office, and other employes on the division.

There is a decided lack of ability to secure information of the thousand and one emergencies that arise on a railroad, by telegraph, as quickly as desirable. This is due, first, to the fact that comparatively few employes on the system can use the telegraph directly, and second, to the fact that the telegraph is slower as a means of transmitting intelligence than its great competitor, the telephone. It takes longer to transmit a train order by telegraph than by telephone. This disadvantage of the telegraph is especially noticeable when one attempts to discuss any subject over the wire by telegraph, even between expert operators; and where it is obligatory to write out the necessary questions and answers in the form of messages to be sent and received by operators, the superiority of the telephone is even more evident.

The telegraph is at its best in handling messages that are comparatively brief, making definite statements or reports or answering definite questions. As soon as one attempts to ask several questions on different phases or points of a subject, in other words, attempts to discuss it, the telegraph becomes a comparatively slow means of communication.

Trouble is also experienced from delay in getting the offices along the line to answer their calls. In case several wires are looped into an office, and the operator is busy, he may not hear the call when made, or perhaps will pretend that he does not, and it is impossible to prove definitely whether or not the call came in properly. Some attempts have been made to meet this difficulty by providing a telegraph selector at each station that would respond to a certain combination of signals and ring a bell for the particular station desired. However, this device has not been used to any extent by the railroads.

There is, also, the trouble experienced in obtaining operators, which in recent years has become a serious problem, especially when times are prosperous. A railroad which depends at present entirely upon the telegraph has considerable difficulty in se-

curing operators of any kind, without much regard for their ability. There has been a great falling off not only in the supply, but in the grade of men who enter this field. Twenty or thirty years ago, the conditions were strikingly different, for the reason, perhaps, that there were not then the many opportunities for men to enter electrical pursuits that there are today. Then there is the influence of the labor organization. Practically all railroads have a strong labor organization of telegraphers with which to contend. In making promotions, the labor union appears always to desire to have seniority in the service made the primary consideration, and ability or fitness for a position the secondary consideration. In general, this seniority idea tends to drive the best men out of the service and prevents the ablest men from learning to telegraph.

The Railroad Telephone Plant

The outside plant necessary in connection with the telephone is substantially the same as that required for the telegraph, except that in practically all cases copper wires are used. Two wires, however, are necessary in order to provide a metallic circuit, and they must be arranged side-by-side on the crossarm and transposed at frequent intervals in order to avoid induction and cross-talk from other circuits. All cables used in looping telephone circuits into offices must have their conductors arranged in twisted pairs, in order to avoid cross-talk.

The great difference between the telegraph and the telephone plants is in connection with the inside plant. Instead of the comparatively simple apparatus already described, the telephone equipment is more or less complicated. There is first the private branch exchange, which has become so important a part of railroad operation in so many places. These exchanges are, in a great many cases, rented from the telephone companies at the usual rates. However, there are numerous exchanges privately owned and operated, the latest type to be used being the automatic switchboard. Arrangements are made to bring into these branch exchanges the telephone lines of the railroad between the different division points and terminals, to facilitate ready intercommunication. Also, in some cases, arrangements are made so that a railroad official can talk from his office over the lines of the railroad company to any subscriber's station in the public exchange system in a distant city or town.

The cost of telephone circuits for use between the exchanges along the line depends, of course, on the kind and the size of

line-wire used. The cost per mile of a No. 9 A. W. G. copper circuit in place, on the basis of fifteen-cent copper, is about $75.00. The cost per mile of a No. 6 A. W. G. copper circuit on the same basis, would be about $150. The latter circuit would give, under ordinary conditions, satisfactory telephone transmission up to 1000 miles, while the former would be satisfactory up to about 500 miles (804.6 km.).

The telephone dispatching and message circuits are the most interesting and peculiar to the railroad service. The provision of a means of selectively signaling the different stations along the line was a problem that took some time to solve satisfactorily. These selectors have different designs and principles of operation. In general, the selection is made by a step-by-step mechanism which responds to a certain number of pulsations or combinations of pulsations sent over the line, making it possible to arrange a large number of selective combinations, and thus signal any given station at will, without disturbing the others. Selectors are now made that are very efficient in operation, and will call selectively as many as 125 stations on the same line. At the stations along the line a special form of telephone set is installed for the use of the operators. These sets have a certain combination of apparatus and wiring that provides a so-called "booster" effect in transmission. This is secured by a switch which is so connected in the circuit that when the operator is talking, the receiver is short-circuited, and when the operator is listening, the receiver is connected directly to the line and the transmitter disconnected. Head telephones are provided so that the operator may have free use of his hands. In the dispatcher's office, special telephone sets are used which are wired like the sets at the way stations, except that breast-plate transmitters are usually provided so that the dispatchers can move about sufficiently in making entries on the train sheets, which are usually of considerable length and width. Some of the railroads have experimented with, and are using with some success, loud-speaking transmitters and receivers for the dispatchers. This apparatus, however, has not been developed to the point where it can be used successfully in all cases. Loud-speaking apparatus is greatly to be desired, as the dispatchers complain quite generally of the hardship of wearing continuously the head telephone and the breast-plate transmitter.

The batteries used at the way stations are in most cases com-

posed of dry cells; they are also used in the majority of cases for the line-battery in the dispatcher's office. These cells are, on the whole, the most economical, as the line current necessary to operate a selector is rarely over 10 milliamperes and in some cases is as low as 1.5 milliamperes. However, small generators are used in some cases to furnish the necessary ringing current; storage cells, also, are used, and both are economical where the circuits are long and there are numerous busy stations on them. In a few cases secondary battery is used at the way stations, but it is not general practise, primary cells being in the great majority of cases the most economical. Wet primary cells are often used for providing the current for the dispatcher's transmitter.

The cost of providing a selector circuit ready for operation under average conditions is as follows:

Cost per station of providing and installing the selector and telephone equipment, protectors and wiring, both outside and inside of the offices, $80.00.

Cost of providing and installing the necessary telephone and selective apparatus, including the battery, in the office of the dispatcher, $250.00. Assuming that a telegraph pole line is already available, the cost of a suitable telephone circuit has already been placed at $75.00 per mile, so that the cost of providing and installing a selective telephone circuit along 100 miles (160.9 km.) of railroad, where there are thirty offices to serve, would be a little over $10,000.

A telephone circuit as described above can be used either as a dispatching circuit or as a message circuit. In arranging for the handling of messages by the telephone, the operator at the terminal office usually remains on the line continuously, thus requiring signaling in one direction only. Often separate rooms are provided for the telephone operators; but in some cases they are placed on opposite sides of the same tables which the telegraph operators use, with good results. The number of messages that can be handled on a telephone message circuit will average twice the number that can be handled by telegraph between the same offices, especially if a typewriter is used in receiving.

Two very useful and time-saving auxilaries which are available with a telephone system are installations of telephones in booths or boxes along the railroad right-of-way at so-called " blind sidings " (where no regular operators are employed, and where there may be not even a station building) and portable telephones for the use of the train crews. Telephones of these

types can be used to great advantage by the trainmen in handling the many emergencies that arise, and are also of material assistance to the dispatcher, in reducing train delays. Order-forms for use of the trainmen are usually provided along with the telephones installed in booths or boxes and, in some cases, special forms of registers are provided in which the order forms are placed so that three copies can be made of all orders transmitted to the trainmen, one copy in each case being given to the engineman, the second copy to the conductor, and the third copy remaining in the machine as a record.

The portable telephone has obvious advantages in the respect that it can be used at any point along the road, by making temporary attachment to the telephone line-wires. Some of the railroads, however, have installed telephones in boxes or booths along the right-of-way every half mile; in such cases portable telephones could hardly be used to advantage. The telephones along the right-of-way are usually connected to the dispatching circuit so that the trainmen can talk directly to the dispatcher. Where telephones are provided every half mile, they are usually connected to a separate line-circuit, and provisions are made at way stations for switching it to the dispatching circuit.

The cost of a booth installed along the right-of-way, with the necessary telephone apparatus, depends on how elaborate an installation is desired; a very substantial and satisfactory installation can be provided for $90.00, but this can be reduced to possibly $30.00. A good portable telephone can be purchased for $12.00.

In addition to the uses already described, there are various miscellaneous ways in which the telephone can be used on a modern railroad. Telephone sets are placed in the observation cars of limited trains and connected to the railroad company's branch exchange, so that passengers can talk to parties in the city from which the train is leaving, up to the time of departure. The telephone is often installed in freight sheds and in freight yards so as to provide a means of ready communication from one point to another. Special types of telephone sets are installed on the desks of officials and so wired that conversations can be carried on with other officials in the same building by ringing a bell as a signal and then simply talking in an ordinary tone of voice into the telephone set, without the use of the ordinary receiver or transmitter. Local telephones are installed in the homes of trainmen for use in calling them for duty, thus saving time and avoiding the expense of employing messengers.

The method employed in handling train orders by telephone contains some points of interest. All figures or names of stations occurring in the order are spelled out letter by letter, both in the giving of the order and in all repetitions; also, in handling a "31" order,[1] the name of the conductor is spelled out. The dispatcher writes the order in his train-order book at the same time that he telephones it to the operator or operators on the line. Each operator who receives the order repeats it back to the dispatcher, the dispatcher underlining each word or number as repeated. In operating a message circuit, the same general practise of spelling out words and figures is followed as in the case of the dispatching circuit. The cost of maintenance of the telephone is always more than the telegraph, for the reasons that the telephone is more complicated and has more equipment. In the author's opinion, specially trained men should always be employed to maintain the telephone station equipment, although on some railroads the section linemen are required to maintain the telephone equipment; the last plan, however, produces in most cases indifferent results, in the author's opinion. In order to maintain properly four selective telephone circuits, having an average length of 100 miles each, at least one telephone inspector should be provided at a monthly rate of $85.00 with expenses, and there should be additional force if there are many telephones maintained at different "blind sidings" along the line, or special apparatus installed at various terminals, private-branch exchanges, etc. All of this expense is practically in excess of what is necessary to maintain the telegraph to handle the same work, although, as already indicated, the telephone handles a great many transactions that were never attempted by telegraph.

Comparative Advantages of the Telephone

The advantages of the telephone are many; some direct, some indirect and some psychological. The first and most important, in the author's opinion, is that it permits direct dealing between the parties desiring to transact business. The superintendent can talk directly with his subordinate; the chief dispatcher can talk directly with the trainmen out on the line, and any two employes can deal directly with one another, if the proper telephone facilities have been provided. This is what might be termed

1. A form "31" order requires the signature of engineman and conductor, whereas a form "19" order does not: see "Standard Code" of the American Railway Association.

the universality of the telephone as compared with the telegraph; every one from the president to the section foremen can use the telephone directly. The telephone, compared with the telegraph, is a great time saver on account of its speed of transmission. Train orders can be handled more rapidly by telephone than by telegraph. This is due to the fact that the orders can actually be transmitted faster over the telephone; also, to the fact that the operators along the line can be made to answer the calls on the telephone bells quicker than their calls on the telegraph. The primary reason for this last condition is the use of four-inch vibrating bells for way-station calling signals, which can be heard from some distance. Again, an operator does not know what is taking place on a telephone line until he comes in on the circuit, while, with the telegraph, the operator by listening can read all that is being sent and, in some cases, can judge as to the relative importance of the calls for his office. A call on the telephone always involves an uncertainty as to what is wanted or who is calling; therefore, in order to be on the safe side, the operator will unconsciously drop any work in which he is engaged and answer the telephone bell when it rings. This peculiarity of the telephone constitutes one of its psychological advantages referred to above. Furthermore, the calling bell is so wired in the circuit that the dispatcher hears it ring, thus removing any doubt as to whether the bell actually rang or not. This is a very important point in favor of the telephone, as it removes any chance for an argument between the dispatcher and the operator as to whether the latter was called.

Since the dispatcher remains on the circuit continuously, the operators along the line can communicate with him without calling, by simply coming in on the circuit and stating whatever information they may have to communicate. On this account it naturally follows that more detailed information is obtained as to train movement, and that the dispatchers can keep in closer touch with their work. In using the telegraph a train dispatcher is not able to transmit his thoughts by one-tenth the speed he could express himself by word of mouth. While a dispatcher cannot send a train order ten times as fast by telephone as by telegraph, he can carry on conversations with operators and trainmen along the line at this rate, which is a great advantage to all concerned. Also, with the telephone, the necessity is removed of operating trains through the medium of a large number of men of varying ability. Then there is

the human side of the telephone system; the men along the line get very much better acquainted over the telephone than over the telegraph, and coöperate to greater advantage. This condition was largely unknown when using the telegraph, and is not the least of the advantages in the use of the telephone.

By the use of the telephone, the field from which dispatchers and operators can be recruited is naturally broadened. It is no longer necessary. on a railroad where the telephone has been installed with a sufficient number of circuits to keep the service intact, to depend on telegraph operators, in other words, specialists. There is, for example, one division on the Pennsylvania Railroad where out of about 400 operators' positions along the line, it is necessary to fill only eight of them with telegraph operators. This is a very important point for consideration in these days when, as already stated, the supply of telegraph operators is not equal to the demand. Also, it is possible to use as a dispatcher an employe other than one who has obtained his experience in the telegraph or telephone service, as, for example, a freight or passenger conductor.

While a telephone circuit is, in most cases, more susceptible to outside influences than the telegraph, experience shows that in heavy weather, heavy fog, mist, rain or snow, less trouble is experienced with the telephone than with the telegraph; and the telephone is affected only to a small degree by earth currents or by the aurora borealis.

Finally, we have for consideration the saving in the operation of the railroad by the use of the telephone. Unfortunately, it is hard to show in all cases a saving, because many of the best-known economies are more or less intangible. One is generally sure that he is saving time by using the telephone, and it seems at least a fair assumption that there is a corresponding money saving. The psychological effects can be capitalized to some extent, but it is generally difficult to do it. In the way of direct saving, the ability of the dispatcher to get his trains over the division quickly, thereby economizing in operating expenses, is the most evident, and easiest to understand. This is especially noticeable in the amount of overtime that can be saved in the pay-rolls of the trainmen and the enginemen. As it is conservatively estimated that the trains can be handled over a division from 10 per cent to 20 per cent more rapidly by telephone than by telegraph, an approximate estimate of the overtime saved can be prepared by considering

a certain operating division before and after the telegraph is replaced by the telephone. For example, on a certain division where the Northern Pacific is now installing the telephone, both for handling trains and for handling the messages along the line, it has been estimated that a saving of about $200 per month will be made in overtime paid to trainmen and enginemen, to say nothing of the other indirect savings of which mention has already been made. In some cases, a direct saving can be made by using a smaller number of dispatchers when handling a given section of railroad by telephone, as compared with the telegraph. For example, there is a division on the Northern Pacific which is made up of four consecutive districts, having an average length of a little over 100 miles each. Part of the year, the four districts can be handled by using two telephone dispatching circuits; but when there is considerable business on the railroad, four dispatching circuits are used. It would be necessary with the telegraph, to handle the four districts by using four circuits at all seasons of the year. As it requires three dispatchers to handle one dispatcher's circuit during the entire twenty-four hours, and as the salary of a trick dispatcher is $155 per month, the abandonment of any of these positions even for a part of the year is a very desirable thing from the standpoint of saving in expenses.

Savings are also made possible by the installation of telephones in booths or boxes at or near small and unimportant stations along the line where operators have been employed, thus resulting in the closing of these stations for a portion of the day, at least, and reducing the number of operators. In some cases, less expensive operators are employed when the telephone is installed; this practise is quite common on some of the railroads, and is done both at the stations along the line and in the offices at terminals and headquarters. In the latter case female employes are often used to advantage, as all that is necessary is a reasonable familiarity with the business to be handled and the ability to operate a typewriter.

Disadvantages of the Telephone

The principal disadvantage of the telephone as compared with the telegraph is its cost of installation and maintenance. However, these increased costs are overcome by the savings that are made possible. Another disadvantage is that the telephone, in the present state of the art, is not adapted, on account of excessive cost, for use on the railroad for any considerable

distance. While there is a circuit about 1000 miles in length in operation on one railroad in this country, at least, this circuit is used entirely as a talking-circuit and is not used for message work. It requires a good margin of transmission to handle messages over a telephone circuit and, according to the author's experience, a circuit equating to more than 26 miles of standard[2] cable should not be used in railroad service; at least, not in connection with handling trains or messages.

While it is possible to construct a telephone circuit 2000 miles (3218 km.) long, or even longer, that would have the proper transmission efficiency, it will apparently be some time before a railroad can justify such a circuit, from the standpoint of first cost and maintenance expense, and benefits derived. The telegraph will probably continue to handle the messages for the long distances, such as 500, 1000, or 1500 miles (804, 1609, or 2414 km.), for a considerable time to come.

The telephone is not as flexible as the telegraph when making patches in cases of trouble on the regular wires. For example, suppose that the entire pole-line is down at some point between two terminals, it is very easy to re-establish a telegraph circuit over some second route, even though it be very circuitous. If the circuit is too long for direct working, repeaters can be cut into the circuit at intermediate points. For example, it is entirely possible for the Northern Pacific to obtain a circuit from the Western Union Telegraph Co. via Omaha, Denver, Cheyenne, Ogden and Portland, and work directly between its St. Paul and Tacoma offices. But it is impossible to establish an emergency telephone circuit for the distance involved in the above example, or for considerably shorter distances.

The telephone requires a much higher efficiency of maintenance than the telegraph. This is not, strictly speaking, a disadvantage. In fact, the telegraph wires and apparatus should be maintained as well as the telephone system, but in practise this is not done except in very few cases. Also, there are more delicate parts in the telephone apparatus, to get out of order, than in the telegraph. The required efficiency of maintenance is not as easy to establish, on a railroad, as might be thought. The telegraph and telephone plant is necessarily spread out over the entire system, without very much of it in any one place; this makes it difficult to secure adequate super-

2. Standard cable has a resistance of 88 ohms per unit (No. 19 A. W. G. metallic) and a mutual capacity of 0.054 microfarad per mile.

vision, and it is not easy to impress upon the different employes who have to do with the maintenance of the plant, the importance of keeping the lines and apparatus in proper condition.

Summary of Relative Advantages of the Telegraph and the Telephone

The following summary presents the respective advantages and disadvantages of the telegraph and the telephone.

The advantages of the telegraph are: (1) Flexibility in handling circuits; (2) simplicity of installation, operation and maintenance; (3) best adapted for long-distance service; (4) least affected by distance, in respect to transmission efficiency; (5) low cost of installation and maintenance; (6) the necessary standard of maintenance is not difficult to secure.

The advantages of the telephone are: (1) Universality; (2) saving of time; (3) rapidity of transmission or dispatch of business; (4) psychological effects; (5) minimum delay in getting offices to answer calls; (6) lack of necessity of trained specialists to operate the service; (7) saving in total expenses of railroad operation; (8) minimum impairment of transmission efficiency in heavy weather.

Applications of the Telephones

As yet very few railroads are using the telephone as much as they could or should. Because many of the economies with the telephone are more or less intangible, railroad managers are rather cautious in authorizing its wholesale installation. They are usually ready to authorize telephone dispatching circuits, as the savings from them are more easily understood than in other applications. In the author's opinion, the up-to-date railroad of the future will handle its operating divisions entirely by telephone, the telegraph being used only for message work for long distances between the terminals and the general headquarters. On the divisions, the typical way office will have no telegraph instruments, and will depend entirely upon the telephone for handling all messages. At all terminal points and important offices along the line, private-branch exchanges will be installed, which will be connected with each other by means of talking circuits, so that any two employes on the same division or adjacent divisions can communicate with one another easily and quickly. Telephones will be installed in booths or boxes along the right-of-way at frequent intervals, such as every half-mile, and the necessary lines and apparatus provided

so that trainmen, sectionmen or any one out on the line can obtain ready communication with persons with whom they may have business to transact. Where portable sets can be used to advantage, they will be furnished to such employes as trainmen, sectionmen, linemen, signal maintainers, etc., so that connections can be made directly to the telephone line-wires at any point along the line. Ample telephone service will be provided at all points, especially where private-branch exchanges are installed, so that all employes having any legitimate need to talk to one another can do so without delay, whether in the same city or town, or at points on the same division, or other divisions, within a possible limit of 1000 miles. Also, the railroads will not forget to provide ample service so that the public can reach certain authorized employes by telephone, promptly, when necessary.

The above outline of the applications of the telephone to the needs of a railroad is not entirely prophecy, since there are railroads in this country already using the telephone, on portions of their systems at least, almost as extensively as contemplated in the foregoing description.

There are four general methods of communication, namely: by personal interview, by letter, by telegraph or telephone message, and by telephone conversation. There are certain business transactions that can best be handled by only one of the above methods; there are others that can be handled by two or more of these methods; and in some cases, by any one of the four. Without doubt there is always one of these methods, as a rule, that is best adapted to any particular transaction. While a great deal of traveling is done by railroad men, there is still, in the author's judgment, a lack of personal contact in a great many of the departments between the man in charge and the men in the field; in other words, there is a lack of supervision. There is probably no lack in the number of letters written; and there is no doubt at all that too many telegraph messages are sent. The telephone as a means of communication is not, however, used as it should be on the railroads in this country. As already pointed out, the local use of the telephone has been well developed in a great many places, and the same is true of its use in dispatching trains; but its universal application as a means of communication, and its substitution for and its use as an auxiliary to the telegraph, have only in a very few instances been carried to a logical conclusion.

DISCUSSION ON "TRAFFIC STUDIES IN AUTOMATIC-SWITCHBOARD TELEPHONE SYSTEMS" (CAMPBELL) AND "A COMPARISON OF THE TELEGRAPH WITH THE TELEPHONE AS A MEANS OF COMMUNICATION IN STEAM RAILROAD OPERATION" (CLAPP), NEW YORK, MARCH 13, 1914.

William Maver, Jr.: I think it may be safely stated that if the telephone had been invented before the telegraph, and had been in use on railroads for train dispatching and the transmission of messages, up to the limit of distance of which it is capable, there would have been very little disposition on the part of railroad managers to displace the telephone by the telegraph, but when the telephone appeared the telegraph was well established on railroads, and its small cost and simplicity have served to give it the stability in railroad service that it has acquired.

The question of the more extended use of the telephone on railroads was under discussion before the Association of Railway Telegraph Superintendents at the Annual Convention in Wilmington, N.C., in 1899, and the chairman of the convention expressed the views of the Association when he said that the railroads as a general thing do not earn large dividends, and they do not care to spend much money on telephone lines. Although the subject of the use of the telephone for train dispatching was mooted in 1899, it was not until 1907 that its use for this purpose on a large scale began, and its employment in this service imperatively demanded the development of means for rendering it practically available, which demand was met by the introduction of selective ringing.

I think the idea prevails that iron has been quite largely displaced by copper wire for telegraph purposes, and that when iron is used in new work it is to give strength to the line. One important claim for the employment of copper wire in telegraphy, in addition to its superiority electrically, has been that when iron, by reason of corrosion, has become valueless, copper wire still has high intrinsic value as junk.

My experience on frequent occasions when I have had the option of using the telegraph or the telephone over distances ranging from 200 to 1000 miles has been quite favorable to the telegraph as a means of quick, reliable and intelligent communication between expert operators, chiefly due to an uncertainty as to certain words in telephone conversations, which frequently called for repetition. My observation of the operation of the telephone in some cases seems to indicate that when it is used regularly for questions and answers, the purport of which is generally understood by both speakers, conversation is easy. I have noticed this particularly in cases where the telephone is used as a means of communication between different sections of large manufacturing plants, where illiterate

workmen exchange information freely concerning the work in which they are engaged. When, however, subjects foreign to this work are broached to them by telephone, they are often at sea. While it is true that Mr. Clapp quite properly stipulates a high factor of transmission efficiency for the telephone circuits for this railroad service, I believe that some, at least, of the success of this service between dispatchers, station agents and conductors may be due to their familiarity with the nature of the subject discussed, although of course the precaution of spelling out the words of train orders, letter by letter, and repeating back the order to the dispatcher, is almost a sure preventive of error.

The fact that telegraph operators require months or years to become proficient is a great disadvantage of the telegraph as compared with the telephone, and the further fact that the labor element utilizes this condition to enforce its demands has, no doubt, been an important factor in forwarding the employment of the telephone for the movement of railroad trains.

Mr. Clapp makes the point that the telephone operator at a station cannot hear what is passing on the line until he cuts in, whereas the telegraph operator can hear everything. Seemingly, there is nothing to prevent the railroad telephone operator from cutting in at times from curiosity. Again, there have been cases in which it was important that the telegraph operator had heard the dispatcher's messages to other stations.

The point brought out relative to the time gained by using the telephone in the movement of trains and in other directions, and the consequent saving in the pay-rolls of train crews, as well as the savings due to the displacement of expensive telegraph operators by less expensive telephone operators in many places, is a strong one, although the aggregate saving thus far does not appear to be great in the specific cases discussed by Mr. Clapp.

The change from the telegraph to the telephone in railroad service is quite a radical one, and has to face the condition that the telephone, like the telegraph, is not directly a revenue producer for the railroad companies, and hence does not always receive the recognition that its importance in the actual operation of the railroad system warrants. Considering, however, the fact that it is only within the past two years that any railroad officials have had the temerity to authorize the substitution of the telephone for the telegraph as a means of communication in steam railroad operation, the progress thus far made in that direction is really noteworthy.

William E. Harkness: The use of the telephone in the transaction of railroad business will be greatly increased in the future, and in many cases it will supersede the telegraph. There are, however, certain classes of railway communications which can be handled more economically by telegraph, so that we need not anticipate the complete elimination of the telegraph

as a means of communication. Whether telegraph transmission in the future is to be performed manually or by machine remains to be determined, but this phase of the situation is at present receiving considerable attention.

Mr. Clapp has given figures covering the average costs of line construction and station equipment on single- or double-track railroads. The amount covering station equipment may be increased to as high as $200 per station on multi-track trunk lines under complete telephone operation where the number of lines entering a way station varies from five to ten. Roads of this class are, however, few.

It is interesting to note that the annual saving in overtime by the use of the telephone on the one division mentioned amounts to 24 per cent on the investment, also that the saving given does not include the saving in time of motive power nor the saving in coal consumption, which are two of many expenses which are indirectly affected. Unfortunately, these savings cannot be calculated in advance when presenting the advantages of the telephone to the railroad management.

It has been found that the train dispatcher operating by telephone is under less strain than one operating by telegraph, and can handle practically double the amount of work he has been handling by telegraph. This in some cases has resulted in the extending of his district, as mentioned by Mr. Clapp. The savings in salaries alone in such a case will approximate $5,000 annually, which is equivalent to 25 per cent on the first cost of the telephone circuit over the two districts covered.

While the cost of telephone line construction is nearly double that of the corresponding class of telegraph construction, it must be remembered that the facilities for communication have been more than doubled. In the first place, the speed of transmission has been increased. The average railroad Morse operator does not send over 25 to 30 words per minute, whereas by telephone the same man will transmit at the rate of 50 to 75 words per minute, the latter rate being in excess of the maximum manual Morse record. One factor having a bearing on this matter, which differs from that of a commercial basis, is the greater length of railway messages.

Secondly, in addition to the two wires being used for telephone conversation, they provide an additional telegraph circuit at an expense of not over $100 for auxiliary equipment for simplexing the circuit: or, if two parallel telephone circuits are available a third or phantom telephone circuit can be secured, capable of good commercial transmission for distances up to 500 miles, at an expense of approximately $500. In one case where this has been done, a saving of $100 per month has been made in long distance tolls at one terminal alone, and no value placed on the time saved or increased use of the service.

The telephone for some time to come cannot compete with the telegraph in handling messages over distances of 1000 miles

[illegible]

[illegible]

[illegible]

to be borne out by practise. We note, however, that in the comparison of costs of inside and outside plant, the facilities provided by a single telephone circuit composed of two No. 8 gage copper wires, have been compared directly with the facilities provided by one iron telegraph wire working duplex or quadruplex, and it seems that it would only be fair to recognize the fact that one pair of telephone wires is capable of supplying a telegraph circuit in addition to the telephone circuit, and that this telegraph circuit may be duplexed or quadruplexed. Also, if there are two similar pairs of wires on a pole, properly transposed, we may obtain from them not only a train dispatching and message circuit, but we may in addition obtain a third telephone circuit and a telegraph circuit; in other words, four circuits from the four wires. The cost of obtaining the additional telephone and telegraph circuit is only nominal.

Therefore, it would be more nearly fair to compare, as far as outside plant is concerned, the cost of one No. 9 A. W. G. wire with the cost of one No. 8 B. W. G. iron wire. On this basis the telephone will appear much more favorably in regard to initial cost.

I have noticed further, that the telephone circuit which has been especially designed for use in the railroad field has been referred to as the so-called "booster," and so that there will be no misunderstanding it would be well to emphasize the fact that it is only so called. It might better be called a "conservation" circuit, for in fact the gain in transmission which is effected, which in amount is in the neighborhood of four miles of standard cable, is due solely to the fact that we eliminate the dead loss which occurs in the ordinary telephone circuit by, so to speak, "talking out" through the receiver at that station, and receiving through the secondary of the induction coil. In still other and more general terms, it delivers to the line, when transmitting, more nearly all of the energy which the transmitting element is capable of producing, and at the receiving station it uses a larger percentage of the energy available in producing the necessary effect in the receiving instrument.

I gather from the statement regarding the use of booths at frequent intervals along the right of way for use in case of emergencies, that it is the usual practise to run a separate pair of wires to which these stations are connected, and to rely on a switching arrangement at an adjacent station at which there is an operator to connect the party to the train line. I am wondering if the intent of this arrangement would be to free the train wires of the load of a multiplicity of stations which are not used except at rare intervals. If so, it would seem more economical and the same result could usually be accomplished by the use of a reliable automatic cut-out switch, either operated by the closure of the door of the booth, or from the hasp of the padlock, to insure that the sets were disconnected from the line when not in use. I understand this is quite common practise with a number of the railroads.

D. P. Grace: Mr. Campbell's paper describes the apparatus for recording the time on trunk lines, and that is particularly applicable in automatic exchanges, but I think it might be of considerable use in manual exchanges.

Regarding Mr. Clapp's paper on the advantages of the telephone and telegraph, the most interesting thing to consider, perhaps, is that, in a measure, the dispatching circuit is an automatic system, in that the supervising operator or dispatcher uses the automatic mechanism for calling the operators along the line. As time goes on, it will be interesting to know how much more use is made of automatic apparatus in the general extending of the telephone system that Mr. Clapp predicts. There is a possibility that the automatic apparatus may be used at the terminals as well as in the dispatching along the line.

Mr. Clapp speaks of the delicacy of telephone apparatus and the increased cost of maintenance over telegraph apparatus. Now, it is true that telephone apparatus as placed in the hands of the subscriber along the line is, as a rule, delicate. The telegraph apparatus, on the other hand, is much stronger. Apparatus to be supplied for a telegraph line, or a telephone line, especially on a railroad, should be very substantially built, and if care is given to designing, I think much of the present maintenance charge could be eliminated.

In many railroad systems where telephone circuits have been used for message purposes, there has been a great deal of trouble due to poor transmission. This has most generally been traced to the lack of knowledge on the part of railroad telegraph people in the operation of these circuits. They have assumed that they could be used much the same as telegraph lines, and have connected into the circuit many miles of rubber-covered wire and iron wire, and have even run these wires through many private branch exchange switchboards, the result being that the transmission was very poor. Wherever there is an extended telephone system along a railroad, there should be by all means a thoroughly competent telephone transmission engineer who can lay out the circuits and see that they are properly connected, so that good transmission will result.

The recent storm has shown the susceptibility of the overhead wire plant to serious damage and interruption of service. Unquestionably, this part of the plant, both among the railroad companies and the telephone companies, must be improved in the near future; but whether it is going to be a case of universal installation of conduits or steel poles or concrete pole lines, is yet to be determined.

Great economies would be possible in the handling of communications, in the handling of railroad trains throughout the country, if there could be some sort of combination or co-operation between the railroad companies and the telegraph and telephone companies. It is easy to see that one conduit line along the railroad tracks between the important cities of the country

would furnish means of communication for all telephone messages and telegraph messages, train dispatching, and the signal line service. If we are looking for economies in the handling of communications, I think that is one very fruitful field that is open to us.

John B. Taylor: One point that I want to raise is the relative ability of the telegraph and the telephone circuits to withstand disturbances from power lines. I ask if in making reply the author will express some opinion upon this subject, as well as upon the relative ability of the two systems to continue service through different atmospheric and wet weather conditions.

In some respects the telegraph has the advantage here, in that it is less sensitive to the extraneous currents, and in other respects the telephone seems to have the advantage, in that there is no definite current above or below which the instrument will operate or become inoperative. The transmitted current may be very small, and still be a good recognizable speech current, while in the telegraph line, if it becomes small, it may entirely fail to actuate the instrument.

W. Lee Campbell: I want especially to call your attention to Mr. Clapp's suggestion that the use of the telephone in railroad service may be extended very much further than most railroad telegraph engineers seem to have contemplated up to date, by the railroads operating their own telephone plants at their terminal headquarters. I know of at least one large railroad which is now commencing this plan, viz: it is buying plants to install at its terminal and division headquarters, and is arranging so that any official, by calling the operator in charge of the message line, can talk direct to any station along the railroad line, and, vice versa, any official who may be out along the line at any station may signal the operator at headquarters and have her call the local official desired and connect the two together. This is something which is only possible, as a rule, where the railroad owns its own plants, because the public telephone companies which rent telephone service object to having any privately owned lines or equipment connected to their systems. I believe there is going to be a very large development along this line, and I believe that it will be a very great factor in converting the telegraph engineers and other railroad officials to the use of the telephone in the place of the telegraph.

M. H. Clapp: Referring to Mr. Maver's statement, in stating as a disadvantage the slowness of the telegraph when discussing a subject over a wire, I imagine that this is largely due to the way one has been trained. I have never discussed many subjects at length over the telegraph, however, I have discussed very satisfactorily many matters over the telephone for long distances. I have always had the impression that the telephone provides a quicker method than the telegraph.

As to the matter of operators cutting in on the circuit, I did not mean to imply they could not cut in and listen on the tele-

phone circuit. The chances are, though, that they do not do this as a general thing, because they cannot attend to other duties if they are cut in on the circuit continuously; in the case of the telegraph instrument, however, they can listen from different points in the room while employed at other work.

As to the matter of saving, I spoke of $100 a month, but I did not mean to imply that this was the only saving; it was given only as an illustration of possible savings. Unfortunately, a great many of the savings made possible by the use of the telephone on a railroad are more or less intangible and hard to express in figures. This $200 I mentioned is an illustration of the tangible saving which we figured out in a special case.

Referring to Mr. Harkness's statement on the advantage in flexibility of the telegraph over the telephone, I had more inmind circuitous routings rather than any condition on the division. I appreciate very thoroughly that, by having a large number, or a reasonable number, of telephone circuits on a division, the system can be made practically as flexible as the telegraph.

I also appreciate that selectors have been used very successfully on telegraph circuits. However, they do not appear to be so generally in use—at least it would seem that the telephone had so many advantages over a telegraph circuit with selectors, that their use in connection with the telegraph has not been considered except in a few cases.

Referring to Mr. Hill's statement, comparing No. 9 copper with No. 8 iron, I appreciate that possibly I did not carry that comparison to a logical conclusion when considering the telegraph superimposed upon the telephone circuit. In my reference to the necessity of a special telephone circuit for the use of employees along the line, I had this more in mind: Where the booths or cabinets in which telephones are placed are being used very frequently, and are stationed every half mile or so, I do not believe it good practise to provide means (even with a switch) of cutting in a telephone on a dispatching circuit. It would no doubt be better to provide separate circuits and terminate the circuits in various private branch exchanges along the line.

Referring to the use of the automatic system on the railroads, I believe that it is entirely practicable, especially in shops and terminals, where the number of telephones that do not need outside connection is large. There is one disadvantage, as I see it, however, in placing the automatic system in general use on the railroad—it is pretty hard to arrange a plan for connecting the long-distance lines to the automatic line.

Relative to power line disturbances affecting the telegraph and telephone, it has been my experience that power lines, electric light lines for example, affect the telephone a great deal more than they do the telegraph. In some cases it requires special study in order to avoid the inductive disturbances.

W. Lee Campbell (by letter): Mr. Clapp infers in his response to the discussion of his very interesting paper that there is

some difficulty in the way of connecting automatic intercommunicating systems installed in railway terminal headquarters with long-distance telephone lines, or railroad message telephone circuits. I am somewhat at a loss to understand whether Mr. Clapp meant by this that the Bell Company, heretofore, has objected to connections between its long-distance lines and either automatic or manual switchboards owned by others, or whether, not being thoroughly familiar with automatic apparatus, he is under the impression that it is more difficult to connect it to long-distance lines or message lines than it is to connect manual switchboards to such lines. Since some members of the Institute may place the latter construction on his remark, I wish, in justice to the manufacturers and users of automatic switchboards, to make it perfectly clear that such switchboards can be and have been, for many years, connected to long-distance lines just as readily as manual switchboards have been. Calls from automatic switchboards to long-distance lines and vice versa are made by the thousands every day.

Donald McNicol (by letter): In view of the title selected for Mr. Clapp's paper, I take it, that, in the main, its scope is intended to include only a comparison of the telegraph with the telephone as a means of dispatching railroad trains, and as a medium of communication between railroad officials and operatives for the purposes of train operation.

The extensive employment of the telephone for the purposes cited, during the past eight or nine years, furnishes conclusive evidence that the telephone method more satisfactorily meets general railway requirements.

The points I wish to touch upon relate to the so-called "message" circuits, and to the efficient operation and maintenance of telegraph lines and equipment, with the object in view of increasing the usefulness of the telegraph.

It is quite possible that the general application of the telephone to take care of the service for which it is best adapted, has diverted attention from the possibilities in the way of increased efficiency of the telegraph.

It is stated in the paper that telegraph operators are scarcer now than formerly, and that the grade of men in this service is below that of the men engaged in the work a few years ago. My understanding is that the available supply of telegraphers has been, during recent years, considerably above the demand, and so far as ability is concerned, it is well known that the average telegrapher today can handle at least 25 per cent more messages per hour than were handled by the average telegrapher of a decade or two ago. It is further stated in the paper that the opportunities which the present-day telegrapher has to enter other fields of activity are much more frequent than 20 or 30 years ago. With reference to the situation here presented, I believe that it is very rarely now, that a telegrapher has an opportunity to get into any other electrical industry, due to the fact that speciali-

zation has rendered him unfit for any but the very low salaried places, such as " helper " or as student, and also to the fact that universities and colleges are turning out thousands of trained applicants for positions in the electrical field. Twenty years ago the heads of most electrical enterprises of any importance were ex-telegraphers, and the telegraph was the most prolific school of engineering. While the present outlook is rather forbidding to the telegrapher, it is very favorable to the telegraph, as it is now possible permanently to avail of the services of the brightest men who enter the service—those who formerly left it after becoming good electricians.

It is also stated that the number of messages that can be handled on a telephone message-circuit will average twice the number that can be handled by telegraph between the same offices. My opinion is that the reverse of this would be nearer correct—even where plain language messages are concerned. In the transmission of code telegrams, telephone handling is practically out of the question. A first-class telegrapher can handle seventy telegrams per hour all day, without hardship, on circuits practically unlimited in length. Telephone message work that I have seen done on comparatively short circuits and under very favorable circumstances, fell far below this figure in performance.

Again, it is stated that as compared with the telegraph, the telephone is a great time-saver, due to the fact that a dispatcher can transmit orders faster by telephone. It is my impression that where train orders are copied by pencil or stylus, the dispatcher generally can transmit by telegraph considerably faster than most operators can form copy sufficiently legible for trainmen to read. This brings to notice the fact that the speed of transmission in either case is determined by the speed at which the person receiving the order can write it down legibly. Undoubtedly a skilled telegrapher can write more rapidly than a trainman or an untrained clerk. These considerations emphasize the fact that the alleged greater speed of the telephone than that of the telegraph, where written messages or orders are concerned, is of no evident advantage.

Certainly, the telephone is a more satisfactory medium for carrying on short-distance conversations, especially between non-telegraphers, and the personal contact through the agency of the voice aids materially in limiting the discord resulting from misunderstanding of intent and attitude, which seems to be inseparable from the activities of train operation.

The paper states that under certain conditions the telegraph circuit is susceptible to disturbances to a greater degree than is the telephone. I ask Mr. Clapp if in this case a metallic circuit telephone line is being compared with a grounded circuit telegraph line.

In recounting the " disadvantages " of the telephone, I see no mention made of the fact that where telephones are used for train wire work, the operator has to remain at his desk with the

receiver to his ear in order to be informed of what is going on, while with telegraph operation, the operator may keep in touch with what is passing over the wire while attending to other duties, and without having to remain near the instrument.

Mr. Clapp says that except in very few cases the telegraph lines and equipment on railroads are not maintained at as high a degree of efficiency as are the telephone wires and apparatus. It is also stated that "the telegraph will probably continue to handle messages for the long distances, such as 500, 1000, or 1500 miles, for a considerable time to come." Those in close touch with the entire subject will undoubtedly agree that this latter conclusion is well founded, notwithstanding that a number of expensive attempts have been made to employ the telephone for this very purpose.

With reference to careless maintenance of telegraph lines and apparatus, it is my belief that herein are great possibilities for betterment, involving a reduced cost per message handled and a faster service. The railroad companies have in many instances availed unstintingly of expert telephone advice, in which they have been industriously assisted by the telephone companies, while the telegraph, even for long-distance work, has been regarded as a necessary evil—something to be dispensed with, no matter what takes its place.

It occurs to me that where there are five million telegrams per year handled on one railroad, with little likelihood of the number per year decreasing as time goes on, the possibility of clipping off half a cent per message in the cost of handling, by increasing the efficiency of the telegraph, should prove an alluring prospect in these days of high aims.

M. H. Clapp (by letter): Referring to the discussion submitted by Mr. McNicol, I think the points made by him are very interesting and some of them are well taken. I believe that there is a great deal in the idea that in our desire to extend the application of the telephone to the railroads, we have overlooked possibilities in connection with the telegraph. However, I believe at the present time more and more attention is being given to the development of the telegraph, especially to automatic telegraphy.

It is difficult for me to agree with the assertion that the available supply of operators has been sufficient during the past few years. There has certainly not been an adequate supply in the Northwest during this period. Of course, at the present time there is very little, if any, trouble experienced in obtaining operators. However, we consider that at present, to say the least, we are not having prosperous times. As soon as business conditions improve, I think we will have serious difficulty in obtaining operators necessary to handle our business.

Relative to the ability of the operators of today, I appreciate that first-class operators can, by the aid of the typewriter and other modern equipment, handle more messages per hour than

was formerly done under less favorable circumstances. However, it has been our experience, and the experience of other railroads in the West, that the average operator is not as competent as formerly.

Mr. McNicol apparently misunderstands the point that I was endeavoring to make in connection with the opportunities for the telegraphers to enter fields other than the telegraph. I made the statement*: "Twenty or thirty years ago . . . . . there were not then the many opportunities to enter electrical pursuits that there are today." In this I was endeavoring to call attention to the fact that two or three decades ago the electrical field was very much limited as compared with the conditions of today for the man who desired to take up electrical work, and that the studying and taking up of telegraphy was one of the few opportunities in this line of work, instead of one of many as is the case today. The result of this condition was that a great many high-grade men entered the telegraph field, and as stated by Mr. McNicol, "twenty years ago the heads of most electrical enterprises of any importance were ex-telegraphers." Also, a considerable number of these men who started telegraphing in the early days rose to important positions in connection with the different railroad companies in this country. I agree entirely with the statement that under present conditions it is difficult for a telegrapher to change to another line of work. However, this does not change the condition that formerly the telegrapher on the railroads was a higher grade man than at present, and, even if he did leave the railroad, the railroad had the benefit of his services while he continued on the system.

The statement is made that operators can send without hardship seventy messages per hour. This may be true in commercial offices in connection with bonus wires and where the messages are short, as compared with those handled on a railroad. In our offices an average of thirty messages per hour is a high one. This is on the basis of handling the messages as they are offered and includes forms, which constitute a considerable percentage of railroad work. Considering now the matter of telephone message circuits, I have watched the operation of several of these circuits and I have yet to find a case where the number of messages handled was not practically double the number handled on the same division or section of line that was formerly handled by telegraph. This statement applies almost exclusively to local or way circuits on railroad divisions, and it is only fair to say that the ability to call in promptly the different way offices along the line is a very important factor in favor of the telephone.

The saving of time in the transmitting of train orders by telephone, as compared with the telegraph, is not in the sending but in the repeating back of the orders. The same order is

*See page 328 of this volume

often given to five or six operators at the same time. Now, it is necessary to have the order repeated back by each operator receiving it. When this is done by means of the telegraph, the order cannot be repeated back by the operators any faster than they can send over the telegraph wire. On the other hand, the operators on a telephone circuit can repeat the order back as fast as they can read it and the dispatcher can underline the words in his order book. Further, in connection with the speed of receiving messages over the telephone, I desire to say that messages can be received by telephone on a typewriter by an expert typist much faster than can be done by the telegraph unless code is used, which would not be practicable in connection with an average railroad office.

In reference to the condition under which telegraph circuits are more susceptible to disturbances than telephone circuits, I had in mind grounded telegraph and metallic telephone circuits. I appreciate that if metallic telegraph circuits were used some of the statements made in my paper in comparing the telegraph and the telephone would not hold true.

The disadvantage in the use of the telephone mentioned by Mr. McNicol, of the operator being obliged to remain at his desk with the receiver at his ear in order to be informed as to what is taking place on the circuit, is really negligible and is not considered by the railroads, except in a few special cases. It is very easy for the operator to cut in on the dispatcher's circuit and ask the dispatcher any question desired. In many cases the operator can, by using judgment, ask questions and obtain answers when the dispatcher is talking to another operator on the line, and not cause any perceptible interruption to the operation of the circuit. Also, in practise the operator really has more freedom when the telephone is used than is the case with the telegraph, for in connection with the former he does not have to be listening for his call on the wire and can work outside of his office, or at any point in the station, as long as he is within hearing distance of the telephone bell.

There is no question that the reduction in the cost of the handling of telegraph messages by half a cent per message would be a very profitable matter to consider by any railroad company. However, I desire to call attention to the fact that on a railroad there is not the same opportunity for cutting down the cost per message that is possible in connection with a commercial telegraph company, for the reason that railroad messages are handled in many cases by operators and agents who have a great many other duties to perform, telegraphing being merely incidental to other work. There are only a few offices handling enough messages and having enough operators so that economies can be effected in handling the business. The five million messages per annum to which I referred in my paper were handled by some 1250 operators.

Presented at the Cleveland Section Meeting of the American Institute of Electrical Engineers, Cleveland, Ohio, March 23, 1914.

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SIXTY-CYCLE SYNCHRONOUS CONVERTERS

BY L. P. CRECELIUS

ABSTRACT OF PAPER

The paper describes some 60-cycle, six-phase, 600-volt, synchronous converters used in railway substations in the suburbs of Cleveland. The advantages of the use of 60-cycle apparatus include standardization of frequency, low cost and high efficiency. The converters are of the commutating pole type and a number of special features of their design are described. The improvement of commutation due to commutating poles makes it possible to use fewer poles and higher armature speed, but this has the objection of increasing the noise, which would have been objectionable in neighborhoods where these machines were used. To overcome the noise the armature ends were sealed up and a shield provided behind the front leads, thereby cutting down the ventilation to a considerable extent. The field windings were compounded in order to hold the d-c. voltage constant, and in order to maintain the power factor of the supply circuit at unity the converters were over-excited to produce a leading wattless current sufficient to overcome the reactance drop. In order to overcome the heating effect due to restricted ventilation and over-excitation the value of 3500 amperes per square inch of armature conductor based upon d-c. output at rating was adopted. To permit of a-c. starting the copper dampers are interconnected between the poles to produce a squirrel cage connection all around the field structure. Extracts from the specifications under which these machines were built are appended, as well as extracts from the contract under which the power supplied to the substations is purchased.

ONE year's experience with the successful operation of 15,000 kw. of 60-cycle, six-phase, 600-volt d-c. synchronous converter substation equipment, establishes a precedent for the use of 60-cycle current for purely railway use upon such a scale. This equipment is installed in four substations located in the suburbs of Cleveland.

The fact that only such apparatus that could be depended upon *without question* could be employed to supply efficiently the d-c. power for the railway, required, in the absence of standard practise in the use of 60-cycle converters for this purpose, a very critical and careful consideration on the part of the purchaser, of the essential details of design.

Extracts from the specifications under which the equipment was manufactured are appended, also extracts from the contract

under which the power supply to the substations is purchased. These contracts are correlated in that the former determined the design of the apparatus best suited to take full advantage of the power company's 60-cycle service offered for sale at cost under certain conditions. Both contracts therefore contain some unusual provisions, a few of the more important of which will be briefly alluded to in the following pages.

Synchronous Converters

The introduction of the commutating pole has been extremely beneficial to commutating apparatus, especially in the case of converters. Affording the means of increasing materially the output per pole, it has caused a corresponding reduction of the number of poles per machine, thus providing a marked improvement in the mechanical design of the 60-cycle converter. More latitude in the width of pole face and spacing of brushes has been secured, thereby working towards the mitigation of the disastrous consequences of flash-overs.

The commutating pole, by reason of its rectifying influence upon the armature conductors at the instant of commutation, has also been the means whereby, at the same time, good commutation is secured at the higher speed resulting from the use of fewer poles. This increase in speed, however, has one serious objection from an operating standpoint, viz., noise. In addition to such noises (current and magnetic) as are inherent in all machines irrespective of speed, and are not especially objectionable, there must be included windage and brush chatter, which increase at a tremendous rate with speed. The operation of several machines, such as those under discussion, in one station, without compensating for this, is simply out of the question, as the sounding of alarms and ringing of telltale bells cannot be heard. Besides having a detrimental effect upon the nervous system of the operators, the noise would soon be declared a public nuisance in the neighborhood. By far the most objectionable portion of the noise is due to high-pitched windage tones, and these have been practically eliminated by sealing up both ends of the armature and providing a shield behind the front leads. Cutting down on ventilation to this extent requires that careful consideration to be given to the size of the armature conductors.

Another important point affecting the temperature of the armature winding is the rapid temperature rise of the conductors lying close to the collector ring taps, which is out of all propor-

tion to that of the balance of the winding when operating converters at less than unity power factor. This heating is not uniformly distributed on either side of the tap, but shifts from one side at leading power factor to the other side with lagging power factor.

It is highly desirable in railway work to hold fairly constant d-c. voltage on converters and the simplest way to do this is to compound the field winding. This has several other incidental advantages, one of which is to lock the converters together through an equalizer switch which holds them in parallel on short circuits, which are frequent upon railway systems. The amount of compounding desired varies with the extent and character of load fluctuations, line drop, etc., but whatever the amount it must be offset with reactance in the supply circuit, and in order to prevent its disturbing influence upon the regulation of the system it must be located at the receiving end of the line. In this case it has been given a low value because of the comparatively steady load and low resistance of the circuit.

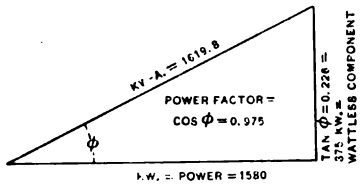

FIG. 1

To maintain the power factor of the supply circuit at unity, as required by the contract [section 9, paragraphs (c) and (d)], calls for over-excitation of the converters to produce a leading wattless current sufficient to overcome the reactance drop. The effect of this is to produce heating in the armature conductors above that caused by the load. When overloading occurs this becomes serious, as may be illustrated as follows:

In Fig. 1 the relations between kilovolt-amperes and kilowatts and wattless component are represented graphically and given the values at which the converters are operated at rating.

Theoretically the ratios between the heating of the winding of a six-phase converter operated as a converter at unity power factor and running as a generator mechanically driven are:

Average value of all coils	0.27 to 1
Coils tapped to slip rings	0.418 to 1

but when the converters are operated at 0.975 power factor as shown in the diagram the heating ratios become:

Average value of all coils	0.313 to 1
Coils tapped to slip rings	0.656 to 1

tors were paralleled with the turbines and the operation of the converters carefully observed. Instantly a wild hunting is set up, the pulsations of which agree in frequency with the speed of the engines, viz., 100 rev. per min., accompanied by violent sparking at the brushes at very light loads, and flash-over takes place at about full load. Thus at any stage the operation is absolutely unsatisfactory. Upon the same generators may be operated, without much trouble in this respect, other synchronous apparatus, including low-voltage converters without commutating poles, although the pulsations from the engines are distinctly noticeable at these machines. It is not at all unlikely that the heavy resulting armature reaction at times of hunting reverses the polarity of the commutating pole, thus becoming the means of exaggerating very much the tendency to flash-over.

In this connection it is interesting to note the agreement between the natural or characteristic period of oscillation of the converters and the pulsations of the supply circuit. This may be determined by Kapp's formula* as follows:

$$N = 24{,}400 \times \sqrt{\frac{P \times p}{Wr^2 \times S \times \theta}}$$

in which

N = natural period in swings per minute
S = revolutions per minute
P = rated output in kw.
Wr^2 = weight in pounds of rotating element times (radius of gyration)^2 in feet.
p = number of poles.
θ = the angle in degrees whose sine is full-load a-c. current divided by a-c. short-circuit current.

Substituting values in this equation we have $N = 90$, which serves to explain that the characteristics of the machines are such as to make them inherently sensitive to pulsations ranging from 90/1.4 to 90/0.7 per minute. The engine speed noted above lies within these values. But notwithstanding this close agreement the fact is, that commutating poles undoubtedly work against converters operating on a-c. circuits subjected to pulsations or frequent and periodic disturbances, and bar from consideration the use of reciprocating units at customary speeds

*Modified formula by Kapp published in *Electrotechnische Zeitschrift*, 1899.

in connection with 600-volt, 60-cycle converters, for this pole is necessary, as pointed out above, for mechanical reasons.

Efficiency

Because of reduced ventilation and the liberal use of copper and iron in the electrical and magnetic circuits, the efficiency of the converters is very high; being,

at	50 per cent full load	91.8	per cent
	75 " " " "	94.0	" "
	100 " " " "	95.0	" "
	125 " " " "	95.5	" "
	150 " " " "	95.8	" "
	200 " " " "	95.0	" "

Best efficiency at 194 per cent full load.

These values are test results and include all losses. Sixty-cycle transformers are also very efficient, and in consequence the over-all conversion loss is low. For a period of one month the sub-station efficiency is as follows:

A-c. input to substations	3,986,880 kw-hr.
D-c. output at converters terminals	3,667,930 " "

$$\text{Ratio} = \frac{3{,}667{,}930}{3{,}986{,}880} = 92 \text{ per cent}$$

This experience in the use of 60-cycle, 600-volt synchronous converters in railway work may be summed up as follows:

1. Pulsations in a-c. supply circuit must be entirely eliminated.
2. The design must include, in addition to the commutating pole, liberal proportions of iron and copper, notwithstanding the high speed.
3. Field dampers must be very low in resistance and bridged to permit of a-c. starting.

The advantages accompanying the use of 60-cycle apparatus are apparent to all and include, briefly, standardization of frequency, low cost and high efficiency.

APPENDIX I.

Extracts from agreement between The Cleveland Electric Illuminating Company and The Cleveland Railway Company, March 29, 1912.

For the purpose of this paper it is only necessary to call attention to paragraphs (c) and (d) of section nine, relating to power factor. This provision imposes a limitation upon the design of

a compound-wound synchronous converter of considerable importance in affecting heating in the armature winding, and consequently the capacity under which standard converters are customarily rated would be much impaired when operated so as to maintain 100 per cent power factor at the primary terminals of the transformers.

SECTION NINE

Paragraph (c)—The Railway Company guarantees that the monthly average power factor at each of the Power Company's supply stations shall be maintained at not less than 90 per cent and it is mutually agreed that if the monthly average power factor at any supply station differs from 90 per cent in any month, then the demand for that month shall be corrected and determined in accordance with the following formula:

Kilowatt demand is measured, divided by average power factor of load, and multiplied by guaranteed power factor of load: And that the demand on each station shall be increased or reduced accordingly, before computing the aggregate demand.

Paragraph (d)—The average monthly power factor shall be determined from the ratio of the sums and differences of the groups of single-phase watt-hour meters installed on each supply circuit, in accordance with the formula, $\frac{W'-W''}{W'+W''} \times 1.732 =$ tangent of average monthly angle of lag, from which both the angle of lag and its cosine, which is the power factor, will be determined.

APPENDIX II.

EXTRACTS FROM SPECIFICATIONS OF SUBSTATION EQUIPMENT

General Information.

The substations (in which the equipment specified below is to be installed) will be located in residential districts of the city of Cleveland and neighboring suburbs, as follows:

* * * * * * * * * * * *

Capacity of Substations.

1. Windermere Substation, three 1500-kw. units as specified hereinafter.

2. Harvard Ave. Substation, three 1500-kw. units as specified hereinafter.

3. West 117th St. Substation, three 1500-kw. units as specified hereinafter.

4. West 25th St. Substation, two 1000-kw. units as specified hereinafter.

Equipment:

The contractor shall furnish, deliver and erect complete in every respect on the purchaser's foundations and ready for use when connected to the purchaser's switching devices, cables and connections:

Nine 1500-kw., 514-rev. per min., six-phase, 14-pole, 600-volt d-c. compound-wound, 60-cycle, synchronous converters, equipped with commutating poles, mounted on self-contained bed plates, including the necessary single-phase, air-blast type static transformers, all in accordance with the following specifications.

Two 1000-kw., 600-rev. per min., six-phase, 12-pole, 600-volt d-c. compound-wound, 60-cycle, synchronous converters equipped with commutating poles, mounted on self-contained bed plates, including the necessary single-phase air-blast transformers, all to be in accordance with the following specifications.

Armatures:

The ventilating ducts, and the general construction of the spider and fixtures, shall be designed with the object in view of minimizing all unnecessary noise such as vibrations, humming and high-pitched windage tones. The converter station in every case will be located in an important residential section of the city where all such noise must be avoided.

The grouping of armature coils per slot in the armature winding shall consist of such an arrangement that the average voltage between adjacent commutator bars shall in no case be less than 13.3 volts, nor more than 14.3 volts.

Equalizer taps shall be brought out from the end of at least every other armature coil and interconnected with all other coils of the same potential, to provide a thorough balance throughout the armature.

The commutators must have the mica slotted or grooved out to a depth well below the surface of the commutator bars.

The d-c. brushes of all converters must be equipped with a suitable brush-raising device to permit of lifting the brushes from the commutator while starting the converters from $\frac{1}{3}$–$\frac{2}{3}$ full-voltage connections, to be provided in the secondary circuit of the transformers.

Field Dampers:

Only the main field poles shall be provided with heavy copper field dampers, properly arranged to provide full damping effect

to the main fields without disturbing in the least the sensitiveness of the commutating pole, in order to provide for the best possible operating characteristics.

Collector Rings:

Because of the high speed, the collector rings shall be equipped with composition copper brushes and suitable pig-tail connections, instead of the laminated type of collector ring brush ordinarily used in the past.

Current and Flux Densities in Armatures:

The current density in the conductors comprising the armature winding must not exceed an average of 3500 amperes per square inch, based upon d-c. output at rating, *i.e.*, considered as d-c. generator.

The flux density in the teeth of the armature core shall not exceed 130,000 lines per square inch, and the density in the core shall not exceed 65,000 lines per square inch, based upon d-c. output at rating.

The current density per square inch of brush surface must not exceed 42.5 amperes at rating.

D-C. Voltage Regulation:

All the converters herein specified shall be compound-wound with sufficient series field effect to produce only approximately constant 600-volt direct-current voltage. The reactance to be provided in the transformer shall be approximately 8 per cent in order to provide for a total reactance of 12.5 per cent, including converter, transformer and leads.

Performance:

After a run of 12 hours at full load at 600 volts, d-c., the temperature rise of the different parts of the converter shall not exceed the following:

Armature	35 deg. cent. rise by thermometer.
Fields	35 " " " " "
Commutator and collector rings	35 " " " " "

With the load then increased to 50 per cent overload (150 per cent rating) at 600 volts d-c. for two hours, the temperature rise of the different parts of the converter shall not exceed the following:

Armature	55 deg. cent. rise by thermometer.
Commutator and collector rings	55 " " " " "

The above shall be based upon a power factor ranging from not less than 0.98 leading or lagging to 1.00, and on 25 deg. cent. for the temperature of the surrounding air and normal conditions of ventilation. In the event of the temperature of the surrounding air differing from 25 deg. cent. the observed rise in temperature will be corrected by ½ per cent of each degree cent. that the temperature of the surrounding air differs from 25 deg. cent.

Insulation Test.

A test to determine the value of the insulation will be made after the converters have been erected by the contractor on the premises of the purchaser, as follows:

The insulation between core and armature conductors must withstand successfully, a test of 2000 volts at 60 cycles, for 60 seconds. The insulation between the frame of the converter and the shunt field circuit must withstand successfully a test of 5000 volts at 60 cycles for 60 seconds.

Efficiency:

The efficiency of both the 1000-kw. and 1500-kw. converters shall be as follows:

150 per cent of rating	50 per cent above full load	95.7 per cent
125 " " " "	25 " " " " "	95.0 per cent
100 " " " "	full load	94.5 per cent
75 " " " "	25 per cent less than full load	93.0 per cent
50 " " " "	50 " " " " " "	90.5 per cent

In testing for efficiency all losses including those in the brushes in commutator and collector ring will be taken into account.

Flash-over Test:

The synchronous converters to be supplied under this contract will be subjected to the following test to determine their freedom from the tendency to flash over. Starting at no load, 100 per cent overload (two times rating) will be thrown on instantly by means of a storage battery and the converter must withstand this test satisfactorily without hunting, destructive sparking, or flash-over. Likewise, beginning with 100 per cent overload (two times rating) the d-c current breaker will be tripped and the load instantly removed. Under this circumstance the same performance with respect to hunting and commutation as above, will be required.

Fittings and Supplies:

Each and every synchronous converter shall be equipped with:

One end-play device (oscillator), d-c. end converter.

One speed-limiting device, a-c. end converter.

One equalizer switch mounted on panel fastened to converter frame.

One suitable shunt field break-up switch fastened to converter frame.

One suitable inductive shunt for commutating-pole field circuit.

One suitable non-inductive adjustable shunt for commutating-pole field circuit.

All necessary leads from brush terminals to equalizer switch, and to suitable terminal block, must be provided, including attachments for connecting in shunts and field terminals.

The collector ring brush collars and all studs on switches and terminal blocks, shall be equipped with terminals.

One shunt field rheostat box with terminal dial.

All the supplies and fittings supplied with each converter must be approved by the purchaser's engineer.

Transformers:

The contract or shall furnish, deliver and erect complete in every respect on the purchaser's foundations, and ready for use when connected to the purchaser's switching devices, cables and appliances, seven single-phase, air-blast shell-type, 60-cycle, 11,000-volt primary voltage, 365-kv-a. transformers.

The contractor shall furnish, deliver and erect complete in every respect on the purchaser's foundations and ready for use when connected to the purchaser's switches, cables and appliances, 28 550-kv-a., shell-type, air-blast, single-phase, 60-cycle transformers, 11,000-volt primary winding.

The primary circuit of all transformers shall be arranged for delta connection and each provided with four 2.5 voltage taps. The secondary circuits of the transformers shall be suitable for diametral six-phase connections for the converters, and each transformer secondary circuit must be provided with $\frac{1}{3}$ and $\frac{2}{3}$ voltage taps for starting the converter.

The outside connections of the primary circuits must be extended by means of suitable leads to terminals in the bottom of the transformer case. All secondary taps shall end in terminals brought to the bottom of each transformer, the whole to make a neat and substantial arrangement for bottom connections.

One transformer of each size will be used as a spare unit and provision for its reception will be made in the substations.

Efficiency and Temperature:

The efficiency and temperature of the transformers shall be in accordance with the best modern practise in respect to the type offered.

Secondary Voltage:

The voltage of the secondary circuit must be suitable for the converters hereinbefore described, as follows: When these transformers are connected in delta relation by means of the outside primary terminals and connected across an 11,000-volt, three-phase line, the converter d-c. voltage shall be 575 volts with normal shunt field excitation.

Insulation Test:

The insulation between primary and secondary winding and the frames and cores of transformers will be required to withstand successfully a test of the following voltages, after erection:

Primary Windings	Secondary Windings.
22,000 volts, 60 cycles for 60 seconds.	2000 volts, 60 cycles for 60 seconds.

Capacity:

At the capacity specified hereinabove, and with the proper amount of ventilation (which ventilation must be specified by the contractor) the transformers must have sufficient capacity to meet the overload requirements of the converters without excessive or destructive heating.

Reactance:

Approximately 8 per cent of inherent reactance shall be provided in the transformers for the purpose of interposing not over a total amount of 12.5 per cent of reactance in the circuit, including the transformer, leads and converter.

Blowers:

The contractor shall furnish, deliver and erect on the foundations in the substations:

Six three-phase induction motor-driven, directly coupled, steel plate blower sets, of the following capacity: 15,000 cu. ft. of air at one ounce pressure.

Two three-phase induction motor-driven sets same as above, with a capacity of 8000 cu. ft. of air at one ounce pressure.

Two blower sets to be installed in each substation; the smaller units to be supplied for the West 25th St. substation.

With each blower set the contractor shall supply an auto-

starter, and the voltage of the induction motors shall correspond to the voltage of the secondary circuit of the main transformers to which they will be connected by the purchaser.

General:

Great care must be exercised in the designing of the equipment hereinbefore specified, to guard against undue noise. As stated above, it is anticipated that trouble will result from the operation of unnecessarily noisy equipment in the substations, which by necessity must be located in the suburbs of the city of Cleveland.

(The balance of the specifications covering foundations, painting and finishing, patents, guarantees, etc., follows along usual lines.)

Presented at the 293d Meeting of the American Institute of Electrical Engineers, Pittsburgh, Pa., April 9, 1914, under the auspices of the Committee on Use of Electricity in Mines.

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MINE DUTY CONTROLLERS

BY HARRISON P. REED

ABSTRACT OF PAPER

The paper is devoted to discussion of the advisable types of control to be used for various mining equipment, particularly in bituminous coal mines. Complexity and theoretical details have been eliminated as far as practicable with the idea of impressing on the reader the need for certain definite features, without going into the theoretical details of these features.

Electric controllers for equipment outside of the mine proper as a rule have to meet different operating conditions than those controllers which are installed underground. The operating conditions are taken up in detail and proper control equipment is suggested to meet these conditions.

The object of the paper is to bring out clearly to the mine operatives the fact that suitable control equipment is just as important as the installation of a suitable motor, and moreover that no motor, however well adapted to the service, will stand up properly if it is not operated with a controller designed and built specifically to meet the existing installation and operating conditions.

THE application of the electric motor to bituminous coal mines has developed so rapidly that there is no section of the industry in which the motor has not been installed. Not only is the application universal, but the use of electricity in coal mines is steadily increasing, principally due to the increased cost of producing steam at the collieries.

The design of satisfactory motor and control equipment for coal mines is a considerable problem, because of the severe operating conditions encountered. The class of attendants usually employed by the mines to maintain electric motors and their accessories, is unskilled, principally because of the location of the mines and the conditions of work. Many changes in help take place for the same reasons, and it is, therefore, difficult to train the attendants and make experts of them. These conditions make it essential that rugged and reliable electrical equipment be installed.

As the use of electricity in the mines has increased, the electric motor for operating mining machinery has been developed much

more rapidly than suitable controlling devices. Only within the past few years have those concerned realized that the selection of a proper controller is as important as the selection of a suitable motor. Too often is the controller given secondary consideration with the result that a good motor may appear to disadvantage, simply because it is not operated with the right control equipment.

At coal mines, motors are used for haulage, hoisting, ventilating, pumping, coal-cutting, tipple or breaker power, drilling, washing, machine shop and blacksmith shop. In the design of electrical equipment for mines, it is necessary to consider carefully the following: explosive dust and gases, continuity of operation, voltage fluctuations and dampness. It is, of course, advisable to install the control apparatus in a locality which is unaffected by sparks or short circuits tending to some derangement of the apparatus. The design, however, must be made so as to minimize leaks to ground, short circuits, etc., which may cause ignition of explosives, of mine gases or of coal dust, with disastrous results. In gaseous mines, arc producers such as circuit breakers, switches and sliding contacts of rheostats must be properly protected, either by breaking the arcs in oil, or by providing explosion-proof cases.

On account of the unskilled attendants in the mines, the electrical equipment receives less than the usual amount of intelligent attention, while on account of the conditions of operation, it should receive more. Much is therefore left to the designing engineer to solve, but on the other hand, much could be done to improve conditions by the employment of a supervising electrical engineer at an attractive salary, whose duty it would be to *see* that better attention is paid to the care and maintenance of the electrical apparatus.

From a safety standpoint, and it is the writer's understanding that we are to follow the slogan " Safety First ", the mine ventilating fan is the most important power-driven machine used within the mining district. Absolute continuity of service is necessary during mining operations to remove poisonous and explosive gases and coal dust from the underground workings. Mine fans are not usually installed within the mines, but at the mouths of the shafts. Mine fan service is, perhaps, the hardest duty possible for a commutator type motor. It runs continually at a constant load, and the mere fact that the load is constant prevents the motor from running light and allowing the brushes to polish the commutator.

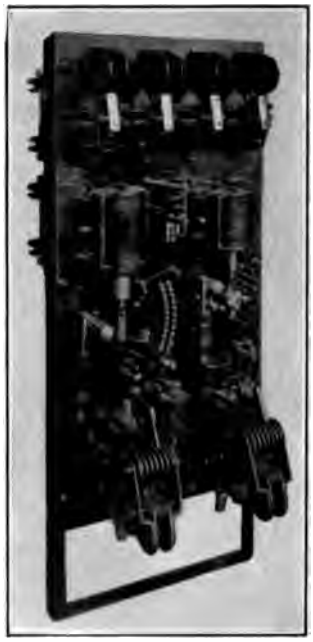
Fan Motor Control

It is still a debatable question as to whether constant or variable speed mine fan motors should be used. Some claim that the fans should be arranged to operate at a peripheral speed of maximum efficiency. This means constant speed; but nearly everyone agrees that variable speed is practically necessary in the mine fan, except for tunnels, subways and old workings. Opinions differ as to whether it is better to use mechanical or electrical means to vary the speed of the fan. Mechanical speed-changing devices such as Reeves variable-speed drives are used, but the tendency is towards obtaining the speed changes electrically, especially when this can be done economically. Speed control of a direct-current motor is easily and economically accomplished by shunt field regulation. The speed control of an alternating-current motor is quite a different problem. A straight slip-ring induction motor with control by resistance in circuit with the secondary is perhaps the most familiar type in this country, but it is open to serious objection because of the rheostatic losses with resultant low efficiency. The commutating-pole slip ring motor is used but very little on account of the complexity of construction, which arises from the necessity of commutating both primary and secondary windings. The commutating-pole squirrel cage machine is more simple, but hardly suitable because of its starting characteristics. It is most advisable from a safety and economic standpoint to have the motor self-starting after it shuts down due to failure of voltage. With a squirrel cage motor, this is difficult to accomplish because of the flywheel load.

The Sherbius system is one which is used extensively abroad, but the writer understands it has not come into use yet in this country. This system consists of a motor-generator set impressing an adjustable frequency lower than the line frequency on the rotor of the fan motor. This system is exceptionally efficient where the speed reduction is not great. The motor-generator set must have a capacity equal, in percentage of the fan motor capacity, to the speed reduction desired. Thus if 25 per cent speed reduction is required, the motor-generator set must have 25 per cent of the capacity of the fan motor. When a speed below normal is wanted, the motor-generator set is used, while when normal speed is desired, the secondary of the main motor is short-circuited after starting. With the Sherbius method of speed control, the losses are minimized and the efficiency is high.

On account of the possibility of frequent failures of line voltage there must be an attendant continually employed in the fan house or a self-starting controller must be installed. The automatic self-starter should be designed so as to permit the operating speed to be set by a proper authority. When the voltage again comes on the line, after failure, the controller should of itself cause the motor to start and resume the speed it was operating at when the voltage failed. This control has been accomplished very effectually for direct-current motors. The starter is automatic and is governed by a simple snap switch. The starting operation is governed by a pilot solenoid and the shunt field is automatically weakened to an amount corresponding to the setting of the field rheostat lever. An example of this type of control is shown in Fig. 1. The speed-setting field rheostat is shown on the center left-hand side of the board. The controller is equipped with a voltage relay so arranged that when the voltage drops below a predetermined value, the relay drops its plunger, thereby opening a circuit causing all of the starting resistance to be inserted in the armature circuit. The motor then runs at a reduced speed until the voltage again becomes normal, when the voltage relay establishes a control circuit which causes the starting resistance to be cut out, again allowing the motor to run at the proper maximum speed. The reason for re-inserting the starting resistance on low voltage is to guard against "flash-overs" at the motor brushes, when the voltage suddenly jumps back to normal. An overload relay is also provided and is especially recommended for shunt-wound motors. This is connected to momentarily open the motor circuit and prevent "flash-overs" when the line voltage falls abruptly and the motor tends to feed into the line. With compound-wound motors, the overload relay is not essential because the series winding weakens the field when the motor acts as a generator. All of these complications in control could be avoided by the installation of separate feeders for the fan motor, or lines of such capacity as would minimize voltage fluctuations, and it is questionable whether the more or less complicated control is justified under these conditions.

Since moisture and dirt are so prevalent in the locality of coal mines, both the control panel and grid resistance are treated with a special moisture-repelling and insulating compound, corrosive bearings are eliminated and all parts necessarily made of iron or steel are enameled or copper-plated.



[REED]

FIG. 1

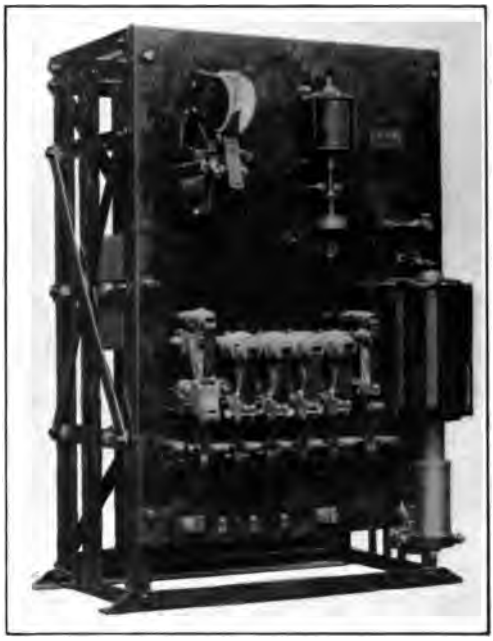


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FIG. 2

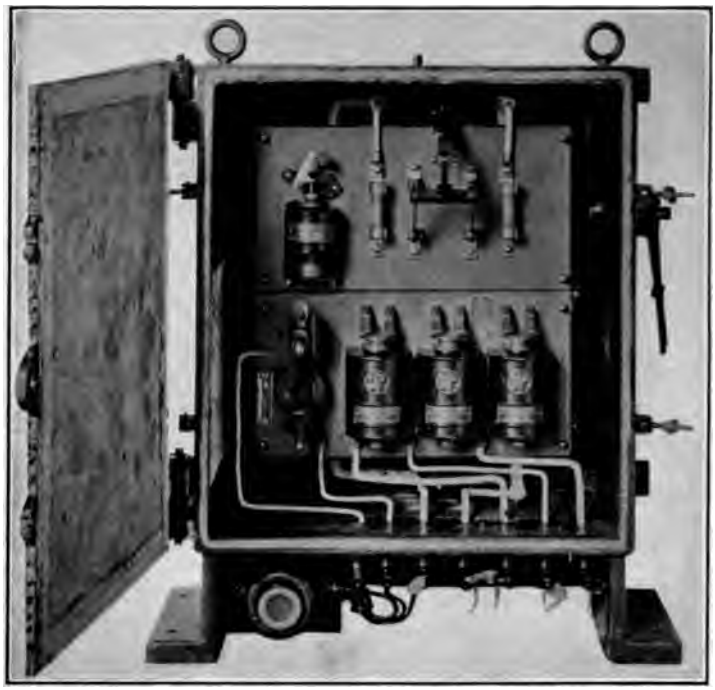

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FIG. 3

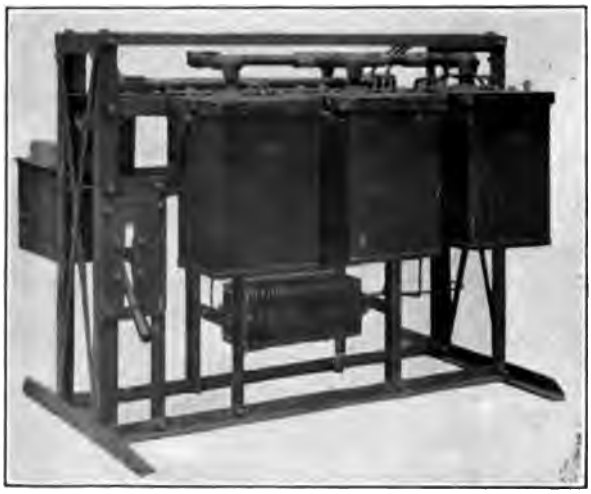

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FIG. 4

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FIG. 5

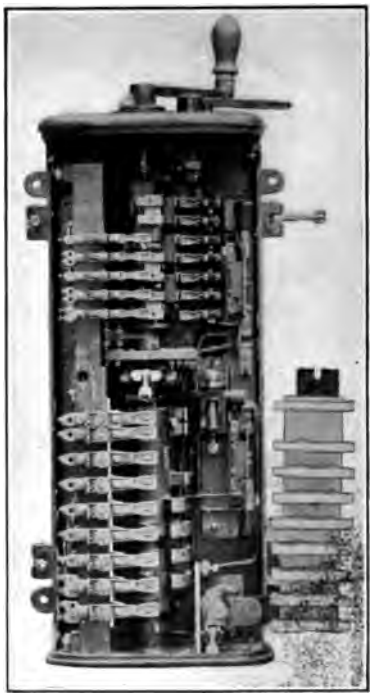

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FIG. 6

Pump Motor Control

Mine pumps are generally installed directly within the mine, because otherwise the suction head would be prohibitive. The pumps are usually of small capacity and should be operated by a self-starter with a float switch in the sump, or arranged to run continuously. The starter should be designed for automatic acceleration of the pump on resumption after failure of line voltage.

Generally speaking, these pumps are placed some distance from the mine workings and therefore explosion-proof motors and controllers are unnecessary, but it is difficult to design electrical apparatus which will stand up under severe moisture conditions prevalent. A typical pump motor starter for direct current, arranged with a voltage relay for protection of the motor against severe voltage fluctuations, is shown in Fig. 2. The starter is specially designed to guard against corrosion and electrical leakages by using non-corrosive metals and by liberal application of an insulating varnish which helps to prevent short circuits as well as to keep moisture from the iron parts necessarily present for magnetic purposes.

An encased, moisture-proof starter is shown in Fig. 3. This is an equipment especially adapted to installations within the mine, even in locations where arcing is dangerous, because it is equipped with a cast iron case, the cover of which is clamped down on a soft gasket, making the case air-tight. The leads are connected to terminals and a special trough is cast in the enclosing box in which is poured a sealing compound covering the junction of the leads and the terminals. At the right-hand side of the box, facing it, is a handle which closes and opens the service switch. The acceleration of the motor is accomplished by limiting the current peaks with series-wound switches.

It might be well to mention here the rather interesting alternating-current controller shown in Fig. 4. This is a 125-h.p. 2200-volt, three-phase, 60-cycle automatic starter for a slip-ring motor. The starter is "explosion-proof" and is mentioned for this reason. The switches are magnetically operated and the circuits are made and broken under oil. The interior of one of the oil switches is shown in Fig. 5. This controller was installed in the Homestake Mining Co.'s gold mine at Lead, S. D. The outfit starts a pump automatically from a float switch. The control circuit is stepped down to 220 volts so that the float switch does not have to handle the high voltage.

Locomotive Controllers

A subject which is occupying much thought among coal mining engineers is the mine locomotive. The tendency is to eliminate the overhead trolley where there are low ceilings. This may be done either by the use of a trailing cable, kept taut by a tension reel, or by the use of storage battery locomotives. The trailing cable was not very popular until the automatic motor-driven cable take-up was developed. Without this device the dragging cable was always in the way. The motor driving the cable take-up is connected across the line in series with a step of resistance. When the cable is to be hauled in, the motor winds it up, and when paying out is required the cable overhauls the motor.

On account of the difficulties attending the use of trailing cables, it would seem that the coming mine locomotive, when not in main entries, will be operated from a storage battery carried on the locomotive. The present trouble with storage battery locomotives is the necessity of laying them up for charging or of having two sets of batteries and charging them at intervals. The battery must be carefully watched and attended. If the batteries could be automatically charged without delay, the usefulness and reliability of the storage battery locomotive would be materially increased. This may be accomplished by the use of an automatic reverse-current cutout, so arranged that when the locomotive picks up the trolley, the battery will be automatically put on charge. If, however, the line voltage is for any reason lower than the battery voltage, the battery will be automatically cut off from the line. The same applies when the line voltage fails, so that the battery will not be discharged into the line. In this way the same locomotives may be used for gathering and hauling trips. This will result in the battery frequently receiving a boosting charge. The nickel-iron battery, which seems the most popular for mine locomotive work, will show its maximum efficiency when so charged.

Manually operated drum controllers are almost universally used for mine locomotives. These are usually of the series-parallel type and there are two prevailing styles, each of which has its advocates. The first operates the same as a standard street railway drum which has two levers, one reverse and one for accelerating. The other style also has two levers as above, but the reverse lever has two positions each side of the "off" position, one for motors in series and the other for motors in

parallel. This latter scheme is advantageous because it is easier to get straight series only, during gathering.

Rheostatic drum type control is sometimes used for underground haulage engines. A typical drum controller for this service is shown in Fig. 6.

For slope mines, the winding drum for haulage is generally installed in the tipple and whole trips of cars are hauled up at once. These winding or mine haulage machines are usually alternating-current motor-driven with secondary control, either by means of a secondary resistance drum or by means of a liquid rheostat. It is sometimes advantageous to be able to change gears for pulling strings of cars in from the sidings. There has been a tendency of late to put in safety cut-offs so that the current to the motor is interrupted before the cars get to the top. Variable inertia plays an important part in the stopping point, and in fact, the variable stopping point sometimes becomes so annoying that a flyball-governor limit switch in addition to the ordinary limit switch is installed, so connected that if the speed is high the governor allows the first limit switch to trip. If the speed is low, the first limit switch is " shunted " by the governor and the haulage may continue until the second limit switch is engaged.

Hoist Control

A straight vertical hoist is used to a limited extent. Almost invariably this type of hoist can be best electrified by the use of the variable-voltage system, because the hoists are short and therefore acceleration is an important consideration. A flywheel is used to store the energy for acceleration. Even with this arrangement, electrification is in many cases of questionable economic value.

A diagram of an equalizer hoisting set is shown in Fig. 7. The hoist is driven by a shunt-wound, direct-current motor, the motor receiving its energy from a motor-driven generator. The motor-generator set has a heavy flywheel which absorbs energy when the load falls below a certain value and gives up energy when the load is above this value. The speed and direction of rotation is governed by changing the field of the generator. When the generator field is weakened while the motor is in operation, the motor operates as a generator and the generator as a motor, thus delivering energy to the flywheel and giving a dynamic braking effect on the hoisting mechanism. Where an alternating-current motor is used to drive the generator, the liquid rheostat

gives very good regulation. The three phases of the rotor are connected to three stationary plates in separate earthenware pots. Above the stationary plates are connected together three movable plates. These are nearly balanced by an adjustable counterweight, the movement of which is controlled by a small induction motor. The small motor receives its energy from series transformers in the main line of the large induction motor and thus the current in the two motors is proportional.

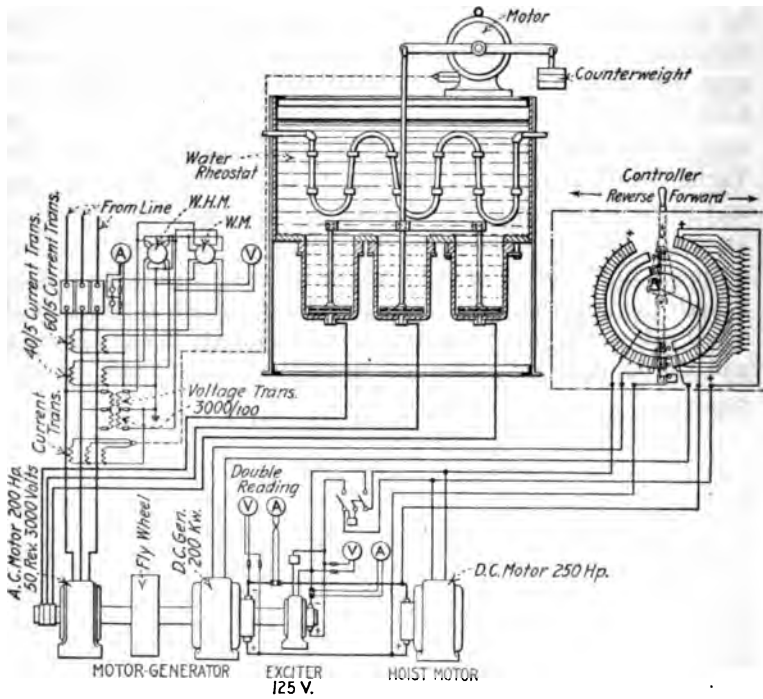

FIG. 7

If the main motor takes more current than it should (depending on the adjustment) the small motor takes more current and raises the counterweight, thereby separating the plates of the liquid rheostat and increasing the resistance in the rotor circuit. This decreases the speed and permits the flywheel to give up some of its stored energy

One case where the efficiency of a vertical hoist was greatly increased by the use of electricity is shown by a change made at the Berwind White Company's mine at Windber, Pa. It was

found impracticable to change the shaft to take care of a larger elevator with more sidings for loading, and an increased capacity of the hoist was necessary because of the increasing production in the mine. A magazine hoist was installed, having a cage with four decks. These decks are loaded by a similar auxiliary cage within the mine. The loading cage is operated by an electric motor and controlled by a simple master switch, so that each of the four decks are brought in succession to the level of the track in the main entry. After the loading cage is full, the cars are run onto corresponding decks of the main magazine hoist and are lifted out of the mine.

Machine Control

Coal-cutting machines are controlled by a plain hand starter fully enclosed. The simpler and more substantial this starter, the better. There is a tendency to design motors for coal cutting which may be thrown directly across the line to start. The writer believes this is a step in the proper direction, because then the control may take the form of a simple hand switch, preferably oil-immersed.

The control of an electric punch or drill is usually a straight hand starter, and the more simple this is, the better.

An important consideration in mine electrical appurtenances is the terminal box. This is used wherever a motor has trailing cables and should be so arranged that putting the plug in the box will close the circuit in oil. An overload should be supplied, which, when it trips, will throw the plug out.

To sum up the situation, mine controllers are just as important as the motors themselves, and the control equipment should receive more thoughtful consideration if our electrical mine installations are to prove successful.

DISCUSSION ON "MINE DUTY CONTROLLERS" (REED), PITTSBURGH, PA., APRIL 9, 1914.

F. L. Stone: There is one line of control on which Mr. Reed has touched very lightly. That is the handling of 2200 volts. This voltage is coming more in use every day, and must be controlled in a safe and efficient manner. The use of oil-immersed switches was the first method tried, but where the operation is frequent and the service severe, as in the case of the mine hoist, either of the slope or shaft type, it does not work out as well as might be hoped. The frequent rupturing of the arc carbonizes the oil, and will eventually cause an arc-over. This comes without any warning to the operator, and usually puts the switch out of commission. Another cause of damage to oil-immersed switches when operated frequently is, that a body of gas will form on top of the oil and finally a hot bubble will arise, and if the proper proportions of air are present a violent explosion will occur, this frequently wrecking the tank, and putting the switch out of commission until repairs can be made. The ordinary oil switch such as is used on a switchboard for control of various circuits may be called upon to operate two or three times a day. A switch to control a hoist operating two trips a minute will operate approximately 1000 times a day in eight hours. In the first case the oil-immersed switch is entirely satisfactory, while in the latter case such information as I have been able to gather seems to indicate that it is entirely unsatisfactory.

The only alternative seems to be a properly designed air-break contactor. Such contactors have been designed, and are on the market, and from everything I can learn are giving satisfactory service. Two of these air-break contactors were installed about one and one-half years ago at the Crow's Nest mine of the Keystone Coal & Coke Company, controlling the primary circuit of a slope hoist of 700 h.p. The operation has been continuous since installation, and even the arcing tips have not as yet been renewed. I have a letter from South America, advising that the air-break contactors are giving most excellent service. One contactor in particular, installed at one of the mines, was put in service early in March, 1912, and at the end of two hundred and forty-four days of operation it had opened the circuit 388,000 times without any renewals or repairs and at a maintenance cost of nil. On the other hand, reports from the same locality on oil-immersed contactors advise that, on account of danger of fire when the oil becomes too much carbonized, it must be renewed every four or five weeks, and between 30 and 40 gallons of oil per switch are required.

From these figures you can readily appreciate that the maintenance of such a switch is a very expensive luxury.

All of the above applies only to switches which are required to operate on a rapid cycle.

Mr. Reed refers to an encased moisture-proof starter to be used in gaseous parts of the mines. I believe it would be better if this casing were built on the principle of the safety lamp, rather than attempt to make it air-tight. Any device of this sort is bound to breathe, that is to say, expel a certain amount of air when warm, and draw in air from the outside when cold. If this action is carried on long enough the quality of the air inside of the box will be the same as that outside, and an explosion might readily be started. Or, when the box is opened for inspection, it will, of course, fill with air from the outside, which may be an explosive mixture. I believe it is generally conceded that it is almost impossible to make a perfectly air-tight joint through which electric wires can be brought. I would like to have an expression of opinion from the Bureau of Mines on this subject.

Mr. Reed in his article makes no detailed reference to control of motors by liquid rheostats. The general trend of the practise seems to be that in motors over 500 h.p. a liquid rheostat should be used for the secondary control. The up-keep of such rheostats should be considerably less than the up-keep of the large contactor panels. The freedom from steps is a very important consideration, and is obtained only in the liquid rheostat. It has been a very difficult problem to design a liquid rheostat with a large ratio of resistance without having the plates so close together that the danger of arcing in event of the motor being reversed is more excessive. This, however, has been accomplished by the use of what virtually amounts to two chambers, one of them of high resistance and the other of low resistance. The low-resistance section is only connected across the slip rings after the motor has attained a considerable speed, and therefore its voltage across collector rings is low. The low-resistance section is cut in by means of a float switch. With such an arrangement the motor could be reversed without any danger of arc-over, as nothing but the high-resistance plates would be in circuit.

Finally, in regard to the part of Mr. Reed's paper referring to mine hoist control, it would seem as though Mr. Reed was of the opinion that a flywheel motor-generator set was extremely efficient. Efficiency is not the aim of the flywheel set, and it should only be used where excessive peaks are penalized or where power station capacity is limited, and it then must be realized that the running of a heavy flywheel throughout the entire day must be done at a considerable expenditure of energy. As a matter of fact, speaking generally, it takes about one and one-half horse-power per ton to operate a flywheel. I will be interested to hear from Mr. Reed as to why he differentiates between shaft hoisting and slope hoisting on the efficiency basis. Personally, I see no difference whatever, except that the control of the shaft hoist is a little more difficult than the control of the slope hoist.

Mr. Reed's statement that the electrification of mine shaft

hoists is of questionable economic value cannot be passed unnoticed. Mr. Reed, of course, would not make such a statement unless he had some figures based on tests and actual observations to back it up. Being particularly interested in mine hoisting, I would deem it a great favor if Mr. Reed would advise us as to just how he arrived at the conclusion that the electrification of mine shaft hoists is of questionable economic value. I have yet to see the case where the shaft hoist has been electrified that it is of questionable economic value.

Sidney G. Vigo: I would like to inquire of Mr. Reed what, in his opinion, is a fair estimate of the largest capacity alternating-current motor that can be applied to a hoist and operated directly on the line of a central station without causing undue disturbance on the system, after taking into consideration the application of the proper controller, as discussed in the paper. This is largely determined, of course, by the size of the station feeding the system, but reference is made particularly to the smaller station, say of 2000 kw., carrying a diversified load. We have had considerable trouble with some of the smaller stations in several instances, by operating motors of 150 horse power directly on the line, using magnetic control. In these cases, faulty regulation of the lighting load was evident.

Graham Bright: High continuity of operation of any apparatus can only be obtained by a constant and systematic inspection. This is particularly true of mine work, since the conditions under which its apparatus has to operate are so very bad and it is difficult to get a good class of operators and inspectors, due to the poor living conditions and isolation of the average mine.

For small pumps up to 20 h.p., the self-starting motor is the best solution of the control problem, as it eliminates the control entirely. If too many motors of this type are placed on a system the first rush of current may prove too much for the generating system, in which case a relay could be provided on some of the motors which would delay their starting for a few seconds so that all motors would not start at once. It seems that the self-starting motor would be a better solution of the problem than the usual control as shown in Figs. 1 and 2. However, where a company has already installed motors that are not of the self-starting type, this control, of course, would be a considerable improvement over the present method of having to cut in and start by hand.

Mr. Reed states that the series and parallel drum controller with the series and parallel feature in the reverse drum is advantageous because it is easier to get straight series only, during gathering. I believe that the straight series position is seldom used, as the motorman will invariably start in multiple. It gives him an easier start, and he can generally start larger loads, since one pair of wheels slipping does not increase the tractive effort of the other pair as would be the case with the motors in series. The real reason for making the series and parallel arrangement on

the reverse drum is on account of the limitation in height. The regular railway type of series parallel controller is too high for mine service, due to the series parallel feature being in the main drum. It has been my experience around the mines that there are few motormen who use the series position very much. The railway type of controller would be a distinct advantage in that the motorman must start in series every time.

I wish to take issue with Mr. Reed regarding his statement that almost invariably the straight vertical type of hoist can be best electrified by the use of the variable-voltage system and that with this arrangement in many cases electrification is of questionable value. It will be found in practise that in a large majority of cases an a-c. wound-rotor induction motor will be used for vertical hoists and will prove the most economical, not only on the basis of first cost but also on cost of operation. Very rapid hoisting, with few or no delays, coupled with restrictions regarding the peak loads that the power company will permit on its system, will only warrant a flywheel equalizer system with voltage control. For very rapid hoisting it is sometimes desirable to use the voltage control system on account of the superiority of the control itself, which readily lends itself to the addition of automatic features. In case the power system can stand the short-time peak loads it is not necessary to use a flywheel, and a synchronous motor-generator set can be used to supply power to the hoist motor. The flywheel and slip regulator losses will be saved and the first cost will be considerably less.

There are no doubt a few isolated cases when it will not pay to electrify a steam-driven hoist, but in the majority of cases a very substantial saving can be made. There are steam hoists in West Virginia at which the cost is over five cents per ton for hoisting from not over 400 feet in depth. Some of these hoists will be electrified in the near future, and it is expected to cut the cost of hoisting to less than one-half of what it is at present.

H. H. Clark: Mr. Stone has asked for a comparison of the explosion-proof qualities of oil switches. The tests that the Bureau of Mines has made have been rather limited in number and have been confined to switches of relatively small capacity. No tests have been made with controllers. The tests were made at 250 volts and with currents no greater than 100 amperes. I have not in mind the exact conditions that surrounded these tests, but about 75,000 breaks were made on each switch while it was surrounded with the most explosive mixture of Pittsburgh natural gas and air. No ignition took place during the tests and it seems reasonable to believe that all switches can be made explosion-proof if the parts are properly proportioned to the service to be taken care of and if the presence of the proper amount of oil in the switch casing can be assured.

From the tests that we have made I cannot say what would happen to an oil controller that is being operated a great many times a minute. It may be that in a comparatively short time the oil level would fall to such an extent that the flash of breaking

the circuit might be exposed and in that case gas would certainly be ignited if it were present. I can say this, however, that in almost every case that we tried it was necessary to renew the contacts several times before the oil level fell to such an extent that the breaking flash was exposed.

H. D. James: Mr. Reed, in the beginning of his paper, makes the following statement:

"Only within the past few years have those concerned realized that the selection of a proper controller is as important as the selection of a suitable motor."

I wish to emphasize this point, as I can recall many personal experiences in which the selection of the motor was such that it was almost impossible to furnish a satisfactory controller. A motor may embody the ideal features for the particular application, but render it very difficult to control this motor in a satisfactory manner. This point has received the attention of both motor and controller engineers with increasingly satisfactory results.

A still further development of the situation has produced the engineer who has the training and experience necessary to study the customer's requirements and select both a motor and controller which will give the best economical results, apart from a purely scientific consideration. This man is commonly known as an application engineer. It is necessary for him to analyze the design characteristics of both the motor and control, and collect the necessary data showing the conditions of load and method of operation that give the best results for the customer. Often the motor can be modified slightly in design, and the controller changed to give a larger output with less strain to the apparatus and decreased power consumption. This is very important from the standpoint of the customer, as the only two items which usually interest him are, first, the amount of capital invested in the apparatus, and second, the cost of power and maintenance.

He is not willing, as a rule, to pay for new and interesting scientific experiments. Occasionally such features have an advertising value, but as a rule, they have no commercial importance. The man who spends most of his time following the design of either motor or control is not usually equipped to make a well balanced application. The electrical industry owes a great deal to the pioneer application engineers, and it is profiting more every year by the increased number of these engineers who are making a special study of each customer's requirements and assisting the customer to solve his power problem so as to get economical operation and increased output.

W. C. Kennedy: In many of these cases, particularly the ones referring to the mine hoists, the equipments are developments, not of the controller alone, but it is a question of the adaptation of the controller, the hoisting machine, and the motor to the conditions of service—a great deal like the ordinary electric-driven elevator. You have to make all three units work together. Sometimes you have to modify the controller

to meet the characteristics of the motor, and sometimes the motor must be modified to meet the characteristics of the controller, and local conditions also affect these different items.

The controller shown in Fig. 1 has been referred to as unsafe for installation in the mine. That controller was discussed under the head of "Fan Motor Control." That is not designed, primarily, to go inside the mine, where it would be subject to explosive gases. In nearly all cases the ventilator fans are mounted at the top, outside, and at the head of the shaft. The main feature of these fans is continuity of service, and to be able to get any speed adjustment desired over a wide range. The amount of air to be delivered varies greatly, depending upon the weather conditions. That controller is designed for use with the shunt-wound motor, having a speed range of about 4 to 1. It is capable of being set to any predetermined point and locked in that position by the mine operator.

The controller shown in Fig. 2 is also not of the enclosed type. It is not so elaborate as the first one, because it is not designed for adjustable-speed motors. It is intended to be used with drainage pumps. These pumps, as I understand it, are located at a point in the mine which is determined by the main operating conditions. They are not usually located down where the cutting is going on, but are mostly on a ventilated shaft, where they obtain the best drainage, and then are connected to the different sumps or drainage wells.

We have built controllers using both air-break switches and the oil-immersed switches, and both types are in satisfactory operation.

The controller shown in Fig. 3 is of the air-break type, tightly enclosed, and I believe operates satisfactorily. We have made some controllers that are not closed as tightly as that, and personally I would be inclined to think this type of control would be better than trying to adapt the principle of the safety lamp. It may be argued that it may collect gas inside, that it is bound to breathe, which is true, but at the same time any electrical device must be inspected, or at least should be inspected, no matter if it is enclosed. There should be a man in every mine, as there is a man in nearly every mill, an inspector, whose duty it is to examine these automatic devices, but I think it would take a long time before that controller could collect an explosive mixture in it.

Mr. Clark has referred to his tests on the oil-break switches, and states that he has tried them up to 75,000 times, and they are still satisfactory. Of course, the ordinary switch will have to operate more than that. We have been very successful with oil-break direct-current apparatus as well as alternating-current apparatus, in situations where there is danger of explosions. This refers to a line of work which is not concerned with mining apparatus, and that is in the powder mill industry. It requires a great number of manually operated controllers, oil-immersed, and they are certainly in a dangerous position

when it comes to the danger of a flash or an explosion, and the only answer I can give is that both types of apparatus are operating satisfactorily.

In regard to the locomotive controllers, I am inclined to believe we would consider series parallel probably better than having the series on one side of the off position and parallel on the other. I think the point which Mr. Reed intended to convey was that we are building both types. Neither of these special controllers is the result of the conceptions and ideas of the designers; they have been cases where we have been called upon to furnish special apparatus, and I know that that drum controller was built at the request of some customer. I think that only goes to show that it would be to the advantage of every one concerned, both the manufacturers and the users, if the mine apparatus could be standardized and made to cover the general requirements, and kept away from these special things as far as possible. That has been done in the Pittsburgh territory among the steel mills, and I know that both manufacturer and user are benefited.

C. J. E. Waxbom: Mr. Reed has mentioned controllers for coal-cutting machines. This is a type of apparatus which is subjected to much abuse in mines. The coal-cutting machines start and stop very often, sometimes under heavy overload, and Mr. Clark suggested the use of oil switches for such starters. Personally I do not believe that oil switches for coal-cutting machines would be practicable, as I am afraid that the carbonizing effect of the oil would be too much. Secondly, I believe that the men around the mine would put in any kind of oil which they found handy.

In order to better the starting apparatus for coal-cutting machines, we have lately devised means whereby a coal-cutting machine is started only once during its operation and then stopped. This is accomplished by means of friction control. The motor is started absolutely under no-load and can be released under no-load. In propelling the coal-cutting machine from place to place, the operator of the machine does not operate the starting box, simply the friction control. In my opinion, that contrivance is one of the simplest and most effective, and I believe one of the most durable, of which we know today. It does away with stopping and starting of the controller, which has been the bugbear of many electricians around the mine.

W. M. Hoen: For fan motor control, alternating-current, a wound-secondary motor is advisable if starting current must be limited. If any great amount of speed reduction is required, and resistance control is used, the loss in resistance is objectionable, but, due to the character of the fan load, this loss will be much less than if the motor were driving a constant torque load. However, its use would be advisable where speed reduction was of rare occurrence.

A squirrel cage motor and its control is the simplest, and as possibly one speed for the majority of mechanical appliances

in mine operation is generally sufficient, a two-speed winding will give good results. The control apparatus can be made simple and the starting characteristics for either speed are suitable for fan operation.

Direct current is usually supplied because of locomotives, and if fan service is supplied from the same source, a separate feeder should be run from the busbars. This would eliminate the greater voltage fluctuation.

If direct current is used for pumping, the majority of the machines will be small, and the proper solution of the control apparatus is to eliminate it and use self-starting motors. They are available in sizes up to 20 h.p. and may be thrown directly across the line.

As to hoist control, drum controllers have been used to a great extent in the past, but with increasing use of magnetic contactors, their increased reliability makes it desirable to use drum controllers only on small, low-voltage hoist motors where the service is intermittent. Except in shafts of very large output and extremely fast work, the induction motor is applicable and can be controlled by contactors when the motors are of average size, and a liquid rheostat can generally be used for the larger motors. This liquid rheostat is very simple, consisting of a number of plates connected to the secondary of the motor, and supported in the upper section in a two-compartment tank. The liquid is a carbonate of soda solution and is kept in constant circulation from the lower to the upper tank by a small centrifugal pump. The level of the liquid in the upper tank compartment which contains the plates, is lowered or raised by means of a hollow weir which is under the hoistman's control. This type has the advantage of simplicity and minimum maintenance.

The voltage control system, as described, is ideal, and is only required where the loads to be hoisted are large, the rope speeds high, and the acceleration and retardation rates very fast. If power conditions limit the permissible peak, a flywheel set with induction motor and liquid regulator as described in paper is proper. If the peaks are not a limiting feature, a synchronous motor-generator set will give all the desirable control features, somewhat decreasing the first cost and the no-load running losses.

Coal cutters were formerly built only for use with direct current, but are now available with induction motors. These can be thrown directly on the line, permitting the use of a single oil switch.

A mine with large power requirements can dispense with direct current except for locomotive operation. This simplifies the control problems and permits oil switches to be used for all control work.

Arthur S. Biesecker: Under "Pump Motor Control," in the last sentence of the first statement is the following: "The starter should be designed for automatic acceleration of the

pump on resumption after failure of line voltage." That, to my mind, is rather a broad statement. I am not very familiar with the bituminous field, but in the anthracite field a very large part of the pumping is now done with centrifugal pumps. If that statement is put in practise, I am afraid that the result would be very unsatisfactory to the operator. If you put an automatic starter of that character on a centrifugal pump, and the power goes off, you lose the water, and then your automatic starter brings your motor up to speed, your runners will run hot, and stick, and then you are in trouble. To my mind that is rather a broad statement.

There are several places around the mines similar to that, where it would be positively dangerous to put on an automatic starter, and the only thing to do when the power goes off, is to let the pump stand still until the pump runner comes back and let him start up the pump again, and see that the conditions are right for starting.

W. C. Kennedy: In regard to the last remark, I think that local conditions would alter that to some extent. I have seen one installation in which a controller, practically of that same nature, was used. It was so arranged that in case the voltage fell below any predetermined point to which it was adjusted the starting resistance was cut back in the circuit, and if the voltage rose again it would automatically accelerate. It was also provided with a feature of control so that, in case of failure of voltage, it would start up again in case power was applied. This controller is in operation, and I have seen the installation at intervals of two or three months, and so far as I know it is all right, but there may be some conditions that would alter that. That pump draws from a sump well about three or four feet below the level of the pump. It pumps against a pressure, I believe, of 20 lb. There is one check valve on the suction line, and I do not believe there is any on the delivery line. So far as the controller manufacturer is concerned, he can make the controller so that it will start up again on the application of power, or not, one way just as easy as another.

The question of acceleration has not been spoken of very much. As usual, there are two types of acceleration, one that is not under the control of the current, and the second is the current-limit acceleration using either series switches or shunt switches with relays. The first is usually known as the constant-time acceleration. We manufacture both types, and under the wide fluctuations of energy which are usually found in mines, we find that the constant-time-element acceleration gives much better results, because the current-limit acceleration is found to give trouble, especially if it is necessary to accelerate a heavy load, with varying voltage, or in case of a variable load. In that case it is practically impossible to use the current-limit acceleration. However, I believe that the voltage condition in mines will gradually improve and that may vary the design of the starters considerably.

Presented at the 293d Meeting of the American Institute of Electrical Engineers, Pittsburgh, Pa., April 9, 1914, under the auspices of the Committee on Use of Electricity in Mines.

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SELF-CONTAINED PORTABLE ELECTRIC MINE LAMPS

BY H. O. SWOBODA

ABSTRACT OF PAPER

The considerable number of mine explosions caused by defects of the Davy safety lamps has encouraged the development of electric lamps. Satisfactory results, however, have been obtained only since the invention of the tungsten lamp, permitting the use of smaller storage batteries.

The general requirements for electric lamps are: absolute safety, uninterrupted production of light for at least one shift, and a foolproof design. Prizes offered by the British Government in 1912 for the best electric lamp, resulted in 197 different constructions being submitted. The first prize was awarded to a German lamp, which since that time has been used with great success all over Europe and which is also being introduced in this country.

The construction of this lamp, consisting of several types for different requirements, and the methods of handling it in actual service, are fully described. Some figures covering repairs and renewals are given.

In concluding, the author mentions the only objection that can be raised against electric portable mine lamps, that they cannot be used as detectors of mine gases, as Davy lamps can, and says that for this purpose devices distinctly separate from the lamp will have to be adopted.

IT IS a well-known fact that a considerable number of mine explosions with their enormous losses of life and property are caused by defects and improper handling of the so-called miner's safety lamps, built on the Davy principle. The Bureau of Mines, for instance, mentions in one of its reports that at least two disasters in this country in 1912 were caused in this manner, killing more than a dozen men, and the Prussian Government states that during the decade from 1902 to 1911 at least 27 per cent of all explosions in the anthracite mines are to be blamed on these lamps. Therefore, it is only natural that attempts to develop a portable *electric* safety lamp were made quite some time ago. Satisfactory results, however, have only been obtained since the carbon filament lamps were superseded by the tungsten lamps. Due to their high economy in current consumption they permit the reduction of the battery to such an extent that the weight and size of the portable lamp does

not prevent the miner any more from moving around freely in performing his duties.

General Requirements

Electric safety lamps must answer the following requirements:

Absolute safety against ignition of mine gases;

Uninterrupted production of a steady and sufficient amount of light for at least one shift;

Absolutely foolproof design.

Besides this, it is essential

To have a simple and durable construction;

To keep the weight at a minimum;

To facilitate the charging and inspecting of the battery.

Safety. Careful experiments conducted by the Bureau of Mines in Pittsburgh and also at Gelsenkirchen, Germany, have shown that the only source of danger in a portable electric lamp is the glowing filament of the incandescent lamp.

Sparks obtained by the breaking and establishing of the electric circuit are not of sufficient strength to ignite mine gases, due to the low voltage and amperage of the batteries used, as long as the maximum short-circuiting current of these batteries does not exceed

100	amperes	for	batteries	with	not	more	than	2.5	volts
85	"	"	"	"	"	"	"	4.0	"
65	"	"	"	"	"	"	"	5.0	"
45	"	"	"	"	"	"	"	6.0	"

Therefore it is not necessary to provide special protection against sparking on the switch and on the connections between battery and lamp.

As the filament under normal conditions is operated in a vacuum and enclosed in a glass bulb, the danger of igniting mine gases exists only in case this bulb is smashed without the filament being broken at the same time, so that the latter continues to glow until it burns out. Several absolutely safe methods can be employed to prevent the filament from glowing after the bulb has been broken, and one method which has been in actual use for a number of years will be described in the course of the paper.

Steady and Sufficient Light. The miners' *old* safety lamps furnish a flickering light of about 0.8 c.p. capacity, which rapidly decreases during the shift to about one-half. This is not sufficient light for the miner to perform his work satisfactorily, and, ac-

cording to the investigations made by Dr. T. Lister of Llewellyn, England, is the principal cause of the special eyesicknesses (miner's nystagmus) with which miners become affected. For this reason it was considered advisable to equip the *electric* mine lamps with incandescent lamps of at least 1.5 c.p.

The only source of electrical energy which will produce this amount of light satisfactorily for at least one shift or approximately ten to twelve hours is the storage battery, primary batteries for such an output being entirely too large for use in portable equipments. Years of development have resulted in fairly satisfactory batteries and it seems, in the present state of the art, that the lead cell, regardless of its weight, on account of its comparatively high voltage and slow drop in voltage while discharging, is the most suitable type.

Foolproof Design. Miners' lamps are exposed to extremely rough handling by inexperienced hands and the least mechanical or electrical weaknesses are liable to result in a failure to supply light. The following are about the most important points which must be observed in a successful lamp:

The lamp must be locked so that the miner absolutely cannot get at any part of the mechanism.

It must burn in any position, even under water, and if dropped on solid material, such as rocks, iron, or cement from a height of several feet, must continue to operate.

The incandescent lamp bulb must be thoroughly protected so that it is almost impossible to break it.

The electrolyte of the battery must not leak out.

That constructions of this character are possible, and in actual use, will be shown later on.

Lamp Designs

During the year 1912 prizes were offered by the British Government for the best portable electric mine lamp and not less than 197 applicants entered into competition and submitted samples. After careful tests extending over several months, the first prize of $3000 was awarded to the makers of the "Ceag" lamp described in this paper. Since this lamp has also been accepted by practically all other European governments and was the first lamp approved by the Bureau of Mines, answering all requirements, and still remains today the only approved *hand* lamp, it might be well to study its construction carefully.

Fig. 1 gives an idea of the general appearance of the lamp.

The incandescent lamp is covered by a heavy glass dome, which is protected by four heavy steel rods held together by a sheet steel roof. A substantial hook is attached to this roof, so that the miner can either stand the lamp on the ground or hang it to a post in the immediate neighborhood of his working place. The bottom part, made of heavy corrugated galvanized sheet steel, contains the storage battery. By turning the upper part on the lower, the miner can turn the light on and off.

The construction of the lamp is easily understood from a section shown in Fig. 2.

The incandescent lamp *l* rests in a socket *n*, which is pressed upward by a spiral spring *o* against another spring *p* between the bulb and glass dome *b*, providing a complete spring support and preventing breakage, even with the most severe shocks. Electric connection is established for one pole through the socket

FIG. 1

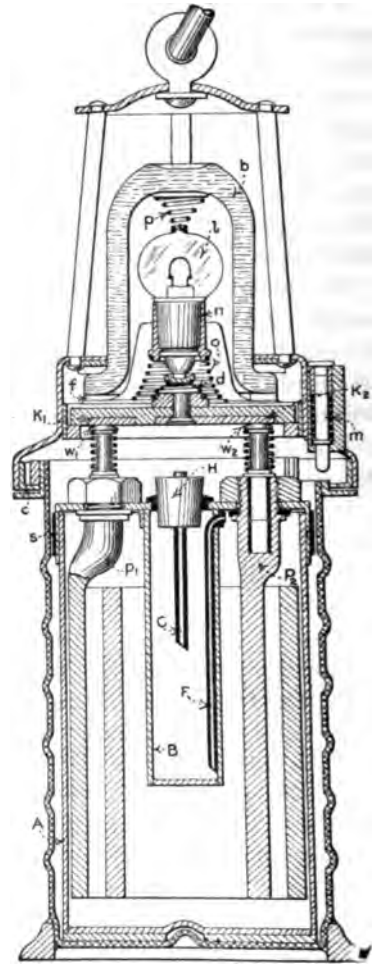

FIG. 2

spring *o*, and for the other pole by another smaller spring *d* inside the socket spring, and insulated from it. In case the bulb breaks, the socket spring pushes the socket upwards, and as the inner spring does not expand as much as the socket spring, the circuit is interrupted.

Lately, another safety device has been added, but is not shown in this illustration. It consists of a fuse, which blows the moment the bulb of the incandescent lamp is broken. This eliminates the possibility of obtaining sparks or getting the filament to glow in case the miner should attempt to push the bulb back into its normal position; it also protects the battery from being short-circuited for any length of time, in case the leads to the bulb have become short-circuited during the accident.

As stated before, the upper part of the lamp turns on the lower part, opening and closing the switch. This rotating movement is limited by a soft iron pin *m*, which acts as a magnetic lock. This pin can be withdrawn in the charging room by a strong electromagnet, and when this is done, the upper and lower parts of the housing separate, and the battery can be removed for charging.

The storage battery consists of a single *round* lead cell with concentric electrodes inside of a celluloid vessel *A* covered with a waterproof lid of the same material. Cylindrical electrodes were given the preference over flat ones, as they are stronger and therefore stand rougher handling. They also warp less, so that in charging, the current density can be increased and the length of time correspondingly decreased. The holes in the terminal sockets contain bushings made of acid-proof metal, into which removable terminals, p_1 and p_2, are fitted. These terminals are pressed upward by the terminal springs W_1 and W_2 against the contact segments K_1 and K_2 of the switch, carrying in this manner the current to the incandescent lamp. Terminals and springs can easily be taken out and cleaned by washing in warm water, a very important point. The use of non-removable springs has been found impractical, as they are very difficult to clean, consequently are liable to corrode and break easily. First-class contact springs, however, are imperative for an uninterrupted light service.

In charging storage batteries gases develop, which must have an opportunity to escape. It is therefore impossible to make the cells airtight. An ordinary opening, on the other hand, would have the disadvantage that the acid would run out, in case a cell were upset, and this would destroy the housing of the lamp. In order to overcome this difficulty, the center of the cell is equipped with a celluloid tubing *B*, which is in communication with the upper part of the cell, where all gases collect, by means of a small side tubing *F*. The gases therefore can pass

from the cell through the side tubing *F* and finally through center tubing *C* into the open, whereas any particles of acid carried along by the gases, will deposit in cylinder *B*. Even if the cell is turned upside down, no acid which may be in cylinder *B*, or any other acid, can escape. In other words, the lamp will burn in any position, without the acid being able to leak out.

The principal dimensions of this lamp are as follows: The weight of the lamp complete is about 5 lb. ($2\frac{1}{4}$ kg.); its height, not including hanger, is $10\frac{1}{8}$ in. (26 cm.); its largest diameter is $3\frac{3}{4}$ in. (9.5 cm.). The incandescent lamp consumes 0.85 amperes at 2 volts. The battery has a capacity of 16 ampere-hours, and the maximum charging current should not exceed 2 amperes. To meet various requirements this standard design is not only made in four different sizes, ranging in weight from $1\frac{1}{2}$ to 5 lb. ($\frac{3}{4}$ to $2\frac{1}{4}$ kg.), but it is also made with two storage battery cells connected in series, resulting for the entire line in capacities ranging from four to sixteen hours of life for one discharge and producing light from 0.75 to 3 c.p.

FIG. 3

Besides this, a number of other modifications have been developed, so that mines can be completely equipped today with electric safety lamps, wherever a permanent wiring in connection with the lighting plant is impossible. Lamps are made for rescue parties, cages, powder magazines, shaft lighting, shaft inspection, loading places, blasting, cars and locomotives (head and tail lamps), etc. A few of these modifications are shown in the illustrations.

The standard lamp, being of the "lighthouse" type, distributes its light uniformly over the entire surroundings. The modification shown in Fig. 3, known as the "trip" lamp, has the incandescent lamp mounted on one side combined with a reflector concentrating the light rays in one direction. This design is mostly used for inspection trips and head and tail lamps for cars and locomotives. It is made in the same capacities as the standard lamp.

The "shaft" lamp illustrated in Fig. 4 is arranged with an adjustable arm, on which the incandescent lamp is mounted, so that the light can be sent in any desired direction. It is made for from 8 to 24 c.p. and from 7 to 12 hours of life for one charge.

FIG. 4 [SWOBODA]

FIG. 5 [SWOBODA]

FIG. 6 [SWOBODA]

FIG. 7 [SWOBODA]

Fig. 5 represents another type of "shaft" lamp, without an adjustable arm. It is made for 8 and 12 c.p. and for 15 and 10 hours of life for one charge.

The lamp illustrated in Fig. 6 is especially suitable for places in which ordinary illumination is not sufficient. It is made for 8 to 32 c.p. and for a life of 7 to 15 hours for one charge.

The lamps so far described were designed to take the place of the Davy safety lamp, which is in use in gaseous mines all over the world. In this country, however, the designer of electric safety lamps is confronted with another problem besides. In a great many mines the crews have and still use "naked" lamps fastened to their caps. On account of the strict enforcement of the mining regulations in recent years, a great many of these mines have been and will be compelled to substitute safety lamps. It is only logical that the men in these mines clamor for a type of electric lamp which is as near identical as possible with the present form of naked lamp. To meet this demand, electric cap lamps have been developed, the batteries of which are carried by the miner on his belt and are connected to the lamp by a well-protected special flexible cord. This lamp is shown in Fig. 7.

The principles of construction of the cap lamp (see Fig. 8) are identical with those of the hand lamp, besides several new features which have been added. One is that the incandescent lamp is mounted inside a parabolic reflector, the opening of which is closed by a lens, instead of being covered with a glass dome; another is a ball joint, permitting the miner to direct the light rays wherever they are needed. The third feature is embodied in the flexible conductors connecting battery and lamp. In case of an accident, there is a possibility that the two conductors may become short-circuited and therefore red hot, eventually setting the insulation afire, if they are made of copper or similar material. To prevent this a special alloy has been prepared, the melting point of which is considerably below the temperature which is required to ignite insulation or mine gas. Consequently, if a short circuit should take place, the conductors would melt and interrupt the circuit, before there could be a possibility of danger.

From the foregoing description, it can be seen that portable self-contained electric mine lamps of this type have passed the first state of development, and if one considers that more than one hundred thousand are in daily use in Europe, ap-

parently producing excellent results, there is no reason why the adoption of electric mine lamps in this country should not make rapid progress in the immediate future. The question whether hand lamps or cap lamps, or both, should be used, is a mere matter of detail, which will adjust itself. European practise has adopted the hand lamp exclusively; the sentiment in this country, however, seems to be in favor of the cap lamp. Men who continually change their location in performing their duties will prefer the cap lamp, leaving both hands free for action; men who stay at work in the same place most of the time will favor the hand lamp, which can be set aside or hung up in the neighborhood, relieving them from carrying unnecessary weight.

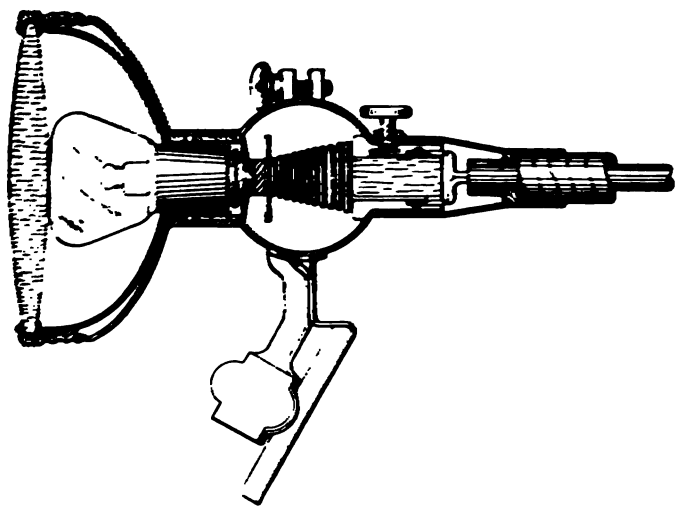

FIG. 8

LAMP SERVICE

When the crew leaves the mine, the lamps have to be delivered to the lamp room for recharging and cleaning. For this purpose the magnetic lock has to be opened, so that the battery can be removed from the housing and placed on the charging rack. The unlocking is accomplished by pushing the lamp lock against the pole pieces of an electromagnet (shown in Fig. 9), which lifts the soft iron pin holding the upper and lower parts of the housing together.

Special charging racks have been designed to receive the batteries. The rack shown in Fig. 10 is intended for 80 cells con-

nected in two series of 40 each. Each circuit is equipped with a switch, ammeter and rheostat, so that the operator can determine the status of the charge at any time. The rheostats are provided with a surplus of resistance, so that less than forty cells in a series can be charged, if necessary. A portable voltmeter with a capacity of about three volts is provided to take the voltage readings on the individual cells. Cells are charged, ready for service, when their voltage reaches a value of 2.6. When more than eighty cells are to be charged, two, three or more racks can be combined, and all the cells can be charged at one time.

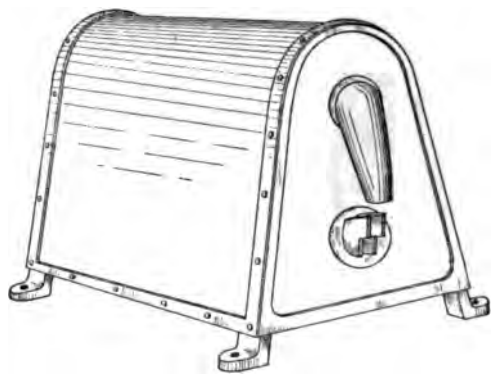

FIG. 9

After the batteries are charged and the contacts and housings have been carefully cleaned, the lamps are reassembled and hung up on special racks, from which the miners remove the lamps, when they begin a new shift.

For mines using a large number of lamps, it is essential that charging, cleaning and repairing be handled systematically and with proper care. For this reason special lamp houses are being erected on the same general principles as those for the Davy safety lamps, but simpler and cheaper, because it is not necessary to make special provision for the safe storage of the fuel, like benzine. The ground plan shown in Fig. 11 represents a lamp house erected for 4000 lamps. It consists of a building about 128 by 33 ft. (39 by 10 m.), containing a charging room with twenty racks, six opening magnets, three small

motors for buffing and cleaning and a small distribution board with a watt-hour meter. To the left of the charging room is the storeroom for receiving the lamps when they are ready for service, and to the right is a small shop for making repairs. Besides this a small room has been provided for a number of benzine lamps, which are being carried for the fire bosses, and on another floor a washroom for the crew.

FIG. 10

Proper care of the lamps has considerable effect on the reliability of the service. One of the large German mines, having several thousand electric lamps in daily use, reports that at first about five per cent of all lamps taken into the mine with the beginning of the shift were returned at the end of the same shift, either burning poorly or not at all. By a careful study of all details in the lamp house and by putting a skilled man in charge of the lamp house work, this percentage has been reduced to less than 1.5, with the expectation that it will soon drop below one per cent. That this last-named figure is not an exception, is verified by

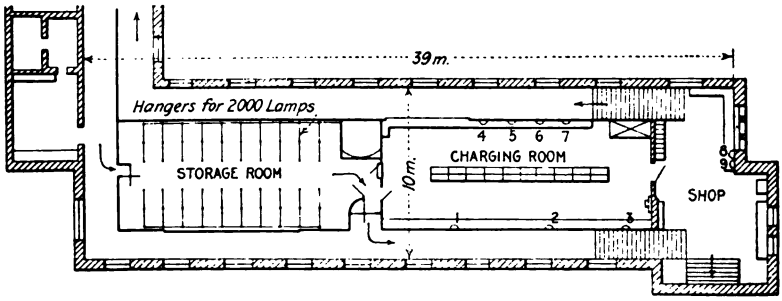

FIG. 11

the Bullcroft Main Colliery Company, Ltd., Doncaster, England. This company has more than 10,000 lamps in daily use and reports the number of defective lamps per shift to be less than one per cent.

The investigation of these defects, if they amount to 1.5 per cent, shows the following:

Defects caused by the incandescent lamps.		
Lamps burning dark	0.6 per cent	
" with broken filaments	0.2 " "	
" " " bulbs	0.2 " "	
Total incandescent lamp defects		1.0 per cent
Defects caused by the batteries		
Batteries leaking	0.1 per cent	
" discharged ahead of time	0.3 " "	
Total battery defects		0.4 " "
Defects due to other causes		0.1 " "
Total number of defective lamps		1.5 per cent

Records covering cost of installing and operating electric mine lamps in this country are not available to any extent, because the number of lamps installed is so far not very large and the time during which they have been in operation is comparatively short. However, it should be possible to form some idea of what can be expected, from the experience in Europe.

Although the first cost of electric lamps is undoubtedly higher than that of benzine lamps, the cost of operation, including maintenance, is claimed to average from ten to fifteen per cent less for electric lamps than for benzine lamps. Whether the same results can be obtained in this country, the future will have to decide. It may be added that the cost of the electrical energy is very small and that the cost of maintenance consists about one-third of labor and two-thirds of renewal of parts, and depreciation.

Especially of importance is the cost of renewing the electrodes of the storage batteries, replacement of complete lamps, which are broken on account of rough handling and accidents, and renewing the incandescent lamps.

The life of the electrodes for lead cells ranges from about 100 to 400 shifts, depending entirely upon the treatment which they receive. At the present time large claims are being made for the alkaline cell, which is supposed to last as long as 2000 shifts. This, however, requires verification by actual tests. Besides this, it must be borne in mind that the higher cost of the alkaline cell, the necessity of using two cells, in series, instead of only one as in the lead battery, and the increase in the renewal of the incandescent lamps, due to the large variation in the voltage, will fully wipe out this apparent advantage. However, the weightiest argument against this claim is the fact that the physical life of mining lamps cannot reach 2000 shifts, as shown

below, and that the natural deterioration of all parts is considerably below this limit.

The replacement of complete lamps which are broken on account of rough handling and accidents undoubtedly varies more or less in accordance with the character of the work performed in the mine. European practise shows that about 0.1 per cent of all lamps per shift are lost in this manner.

The incandescent lamp renewal already has been expressed in figures, in connection with the reliability of service. Excellent results have been obtained, the average life of the lamps being approximately 1000 hours.

From the lamp designs and the lamp service as described above, it can be seen that the development of the portable electric mine lamp has made rapid progress during the last few years, and since, up to this writing, no explosions have occurred wherever installations have been made, it can be said without exaggeration that the electric mine lamp is a success and that it is bound to be adopted more and more.

Of course, as is the case with any new appliance, objections have been raised against the electric mine lamp, especially, because it does not detect inflammable gases as the Davy safety lamp does. There is no doubt that this detail will be overcome in the near future, as there are several principles which can be used for the construction of mine gas detectors. In fact, the German Government only lately has ordered several hundred of these devices, constructed in accordance with the directions of Dr. F. Haber on the acoustic principle and known as " mine gas whistles." These will be distributed to the various mines for a thorough trial.

DISCUSSION ON "SELF-CONTAINED PORTABLE ELECTRIC MINE LAMPS" (SWOBODA), PITTSBURGH, PA., APRIL 9, 1914.

H. H. Clark: The first requirements of portable electric lamps are safety, and the capacity for uninterrupted production of a sufficient amount of light. I wish to emphasize, however, that from the viewpoint of the mine operator, a lamp to be successful must be able to operate day after day with a reasonable amount of repairs and replacement. If this is to be accomplished the lamp battery must be a very sturdy affair. Failure of the battery plates will result in annoying delays and expensive repairs. A dependable battery is indispensable to satisfactory performance.

Another part of the equipment that is most important is the lamp bulb. The cost of replacing the lamp bulbs will be one of the largest items in the cost of maintenance. This cost will be in inverse proportion to the life of the bulb. So far as I have been able to learn, the manufacturers of miniature lamp bulbs have not in the past given much attention to developing the life of the bulb. Up to the present time the demand for battery lamp bulbs has arisen from the extensive use of dry battery flash lamps. The requirements of this class of service are apparently not the same as the requirements of the class of service that we are now discussing. At all events, the life that flash lamp bulbs give has not impressed me as being as long as the users of mine lamps have a right to expect. Reports from abroad lead us to believe that mine lamp bulbs in use there have a life of 500 to 1000 hours, and I presume that no American manufacturer would admit that he could not make as good bulbs as are produced in Europe. The question of bulb life was one of the first problems that the Bureau of Mines took up in connection with its investigation of portable electric mine lamps. The cooperation of bulb manufacturers was sought, and they are now undertaking to ascertain the requirements of mine lamp outfits for the purpose of producing longer-lived bulbs.

Just now the electric cap lamp seems more in demand than the hand lamp for mine service. The cap lamp requires a flexible cord connection between the battery and the head-piece. The design of this cord and method of protecting it from abrasion where it is joined to the battery and to the head-piece is an interesting problem. So far as I am aware, we have no European precedent to guide us in designing this cord because cap lamps have not been developed abroad. I have no doubt, however, that as the result of experience in actual service, that part of the equipment will be developed satisfactorily.

The design of the head-pieces of cap lamps is a matter that should not be overlooked in specifying the requirements of mine lamps. It is important that head-pieces should be designed and constructed so that cord replacements can be readily

made. A most important feature in head-piece design is distribution of light. The light cast should be free from black spots and from sharply contrasting areas of bright and faint illumination, and it is especially desirable that the stream of light thrown out by the reflector should be so broad that shadows are barely discernible on either hand or on the roof or floor.

Mr. Swoboda's paper makes several references to candle power. I should like to ask him whether these figures refer to average candle power over the stream of light, or to measurements made otherwise, and whether with or without a reflector.

Mr. Swoboda mentions an average life of bulbs of 1000 hours. This is a most encouraging and significant statement, and I should be glad to have Mr. Swoboda tell us from what source this information was obtained.

H. H. Smith: It is gratifying to see that the storage battery miners' lamp is finding its place on the programs of technical meetings in this country. It appears from what Mr. Swoboda has said that in Europe they have advanced with the miners' lamp further than we have in America. He has also pointed out that the development has been along quite different lines. The portable lamp which contains the battery within its case offers quite a different problem from that of the lamp used as a head-piece with the battery separate.

I feel that it is necessary to take issue with Mr. Swoboda with reference to his attitude toward the alkaline battery for this class of service. On one of the slides shown on the screen, only a part of which is given in the paper, there was a table of operating costs in which you may have noticed that something over 20 per cent is charged to battery renewals and replacements, and about 35 per cent to attendance; or altogether more than half the cost of operating the lamps. The alkaline battery has advantages along these lines which I believe will tend to decrease these items of cost so as to more than compensate for the higher cost of lamp renewals claimed by Mr. Swoboda—as to the magnitude or importance of the difference in lamp life I am not at the present time prepared to say.

It is claimed in the paper that a battery life of 2000 shifts is of no value because the life of other parts of the lamp is less than that. Inasmuch as the battery is a distinct unit separable from the rest of the apparatus, it is not clear why full use cannot be made of its longer life, the value of which is important because the cost of the battery is approximately half the cost of the entire outfit.

In regard to maintenance, we all know how carefully a lead battery must be handled in order that it may not be overcharged or overdischarged. The charging board recommended for use with the alkaline battery is so arranged that no meter need be used in connection with it, no rheostat need be adjusted and batteries are simply slipped under a pair of spring contacts and

left there as long as desired. It makes no difference if it be left there longer than is necessary or for a shorter time than is required, so far as the life of the battery is concerned. Upon a battery being withdrawn from the board, a resistance is automatically substituted for the lamp, which is designed to maintain constant the current flowing through the circuit, so that a battery can be slipped beneath the spring contacts or withdrawn without any further attention to the board being required.

I have here a battery in its metal container which is designed to be strapped at the miner's waist in the ordinary manner. The cover of the container is secured by means of a hasp and locked with a padlock or, if desired, by means of a magnetic lock. The cord from the lamp is connected with the battery by means of a special plug which fits into a corresponding socket on the cover of the lamp container. When the plug is inserted it is automatically locked by means of a spring catch and it cannot be again removed until the cover is unlocked and opened and the catch released from beneath. The lamp remains lighted, of course, as long as it is in the miner's possession.

The safety devices are similar in effect to those which have been already described. The battery, to be sure, is made up of two cells, but inasmuch as there are only two cells and the containers are metal, the two adjoining poles that are connected together to throw the cells in series are grounded upon the cans and the cans are positively connected with one another, so that no insulation is required either between the cells or between the cells and the container. The battery, therefore, acts as a single unit and may be treated as such.

The cells are rendered unspillable by means of the special valve construction. The valve stem extends to the center of the cell, at which point it is open for the emission of gases. The normal level of electrolyte is below the center of the cell, and therefore, in no matter what position the cell is held, the end of the valve stem is never submerged.

The electric lamp is a boon to the miner and is likewise desirable from the standpoint of the mine operator. It is inevitable that its use will in time become universal. It is, therefore, our plain duty to ourselves and to all others concerned to work together for this end.

R. C. Burrows: In regard to the comparatively high voltage and slow drop in voltage during discharge of lead cells, I would like to call attention to the lead cell using a paste electrolyte. This type of cell does not have the slow voltage drop during discharge that is characteristic of the lead cell using a liquid electrolyte. This is due to the increased internal resistance of the cell with discharge. In the cell with which I have had experience, this increase in internal resistance is not very objectionable: in fact, the discharge characteristic curve lies about half way between that of the lead cell with a liquid electrolyte and the alkaline

cell. There is on the market at the present time a very cheap lead cell outfit using sawdust saturated with sulphuric acid as an electrolyte. This little battery, as far as I have gone with it, shows up very favorably as to discharge characteristics and, with its low renewal cost, should meet a demand where breakage is high.

As to advantages of the alkaline cell as outlined, the necessity of using two cells in series is not serious from the standpoint of increased weight and the life of the incandescent lamps might possibly be increased by discharging the battery through rheostats until the voltage reaches a fairly constant value.

Regarding the figure of 1000 hours life for incandescent lamps, it is a fact that a lamp may be made to live a thousand years, a thousand hours, or one hour, all depending upon the efficiency at which it is burned. The present tungsten lamps would live indefinitely if they were burned at an efficiency equal to the best operating efficiency obtainable for the old carbon lamp. The life of incandescent lamps, then, is dependent on the efficiency at which they are burned and the most economical efficiency must be determined from a consideration of all the factors involved, such as fixed charges, interest, depreciation, renewal of lamps, cost of energy, etc. In fact in practically every case with a tungsten lamp, the greatest economy of light production is obtained when they average 600 or 700 hours instead of 1000 or more hours, as is at present the practise. In determining the length of life of incandescent lamps with these small outfits, we must consider the total cost of the light production and the effect of the lamp efficiency on the weight and cost of the battery. The total cost of light production is not given a great deal of consideration as a rule, but it is nevertheless of importance in this case. These small batteries are only about 50 per cent efficient, so that the effect of decrease in lamp efficiency on the output of the battery should be multiplied by two in determining the most economical efficiency. The fixed charges are high, due to the rapid depreciation of the cell, interest on investment of the outfit and housing, attention necessary, cleaning, etc. If the life of the incandescent lamp had been determined at 1000 hours, considering the cost of incandescent lamp renewals and energy alone, then, the life of the lamp should be somewhat less than 1000 hours, taking into consideration the fixed charges. If the ratio of fixed charges to the cost of the incandescent lamp were eight to one, the most economical life would be about 300 hours, instead of a thousand hours as stated by Mr. Swoboda. In fact, this figure of three hundred hours was adopted by the Bureau of Mines in their proposed specifications. The ratio of eight to one does not seem to be particularly high. For instance, with the cost of lamp as 35 cents, the fixed charges would be $2.80 per thousand hours burning, or for about one-third of a year.

To increase the life of the lamp from 200 hours to 1000 hours

means approximately 40 per cent increase in the ampere-hour capacity, or from 30 to 40 per cent increase in the battery weight and cost.

I might add that in a case I have in mind, the Ceag lamps for the same total lumens weigh nearly twice as much as an American outfit which uses a lamp of high efficiency with a life of three hundred hours.

H. O. Swoboda: Answering Mr. Clark's question regarding candle power measured, this refers to the lamps *with* reflectors. I received this statement from the manufacturers of the Ceag lamp.

Regarding the life of the incandescent lamps, the same manufacturers make the claim of having had lamps burn one thousand hours. The same statement is also made by Mine Assessor Schorrig of the Prussian Government, in one of the papers which he delivered in Germany last year.

Regarding the alkaline battery, mentioned by Mr. Smith, I found that two cells are undesirable on account of the complicated connections. A single cell is much simpler in this respect. The alkaline battery is also more expensive, as far as first investment is concerned. This point has to be considered very much, because the lamps in actual service are destroyed very rapidly and have to be replaced very often. For instance, if the first investment should be doubled by using alkaline batteries, it would mean that the depreciation charges would have to be increased also one hundred per cent and that will counteract, to some extent, the advantages which are claimed from charging without instruments.

Regarding the electrolyte used in the lead battery not being a liquid, I wish to state that the electrolyte of this battery (Ceag) is a liquid. It is common dilute sulphuric acid, such as is used in any storage battery.

Presented at the 293d Meeting of the American Institute of Electrical Engineers, Pittsburgh, Pa., April 10, 1914, under the auspices of the Committee on Use of Electricity in Mines.

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THE DEVELOPMENT OF THE ELECTRIC MINE LOCOMOTIVE

BY G. M. EATON

ABSTRACT OF PAPER

The paper traces, largely by means of pictures, the course that has been followed in developing the mine locomotive to its present condition. The paper is limited to locomotives for operation in coal mines. The two main factors which have directed the development are, first, the demand for increased entry capacity, and second, the exploitation of thin seams. The early machines were high, and of irregular outline, whereas later machines are compact and strong, yet accessible, and easily inspected and overhauled. Various types of framing are illustrated. Locomotives with two and three axles in rigid wheel base, and also tandem locomotives, are shown and described. Reference is made to various methods of connecting the motors by which the adhesive weight is used to full advantage. Gathering locomotives, with vertical and horizontal reels, both axle-driven and with independent electric drive, are illustrated, and some of the problems of gathering work are briefly discussed. There is also brief reference to various types of motors with different methods of lubrication, as well as some reference to sleeve vs. frictionless bearings. The paper closes with a few tendency curves, and attention is called to the lines of future development which these curves apparently indicate.

THE evolution of mine haulage has been directed at every stage by the demand for increased capacity. This clamor for more tons at the tipple is successively relegating to the discard, both man and animal haulage.

Available headroom plays a close second to output requirements in molding the development of the locomotive for coal mines. Wherever the seam is too thin to permit free passage for the mule, the electric locomotive is the logical solution, and as thicker seams are worked out the field must become more and more monopolized by this type of motive power.

The thin seam, however, is not the only logical field for mine electrification. In fact, the earliest applications of mine locomotives were made for service in thick seams, where the chief aim was increased tunnel capacity.

Fig. 1 shows the first locomotive supplied for mine service in

1896 by one of the large builders of this class of machine. It weighed 43,550 lb. (19,754 kg.) and was equipped with two 75-h.p. motors driving through double reduction gearing and side rods. The block displacement of this machine, *i.e.*, length × height × width = 582.5 cu. ft. (16.5 cu. m.). Block displacement divided by h.p. = 3.88 cu. ft. (0.114 cu. m.) per h.p. A modern machine equipped with the same capacity of motors would have only 231 cu. ft. (6.48 cu. m.) block displacement or 1.54 cu. ft. (0.043 cu. m.) per h.p.

This is a measure of the increased demand for space economy in mine locomotives. This particular machine, shown in Fig. 1, was scrapped April, 1913, after 17 years of service.

Fig. 2 shows a locomotive produced in 1913 and is presented to emphasize the radical improvement over Fig. 1. A few of the main features wherein this improvement lies, are listed below:

1. Electrical equipment designed for mine service.
2. Staunchness of general construction.
3. Maximum protection of apparatus, without sacrifice of easy inspection.
4. Single reduction gearing.
5. Low height.
6. Short overhang.
7. Compact design.

All these features may be summed up as those contributing to produce a machine that will do its work reliably with a minimum of out-of-service periods.

Very few locomotives of the scraggly outline shown in Fig. 1 were put out for coal mining service. It became evident at an early stage of the development that a mine locomotive must be capable of withstanding severe collisions, and must sustain a minimum of damage from falling roof and similar emergencies. The locomotive design, therefore, soon settled down to an iron-clad machine with motors under cover, and virtually under an inverted box. This was for many years considered the ideal and only way to build mine locomotives, and is still thus regarded by some today. Cast iron was the almost universal material employed in the locomotive framing.

Fig. 3 and 4 show typical machines of the period, the first with frames inside the wheels, and the second with frames outside the wheels. Thus far the locomotive was used for nothing but main haulage, animal haulage being practically universal for gathering. This was a rather long-lived stage in the develop

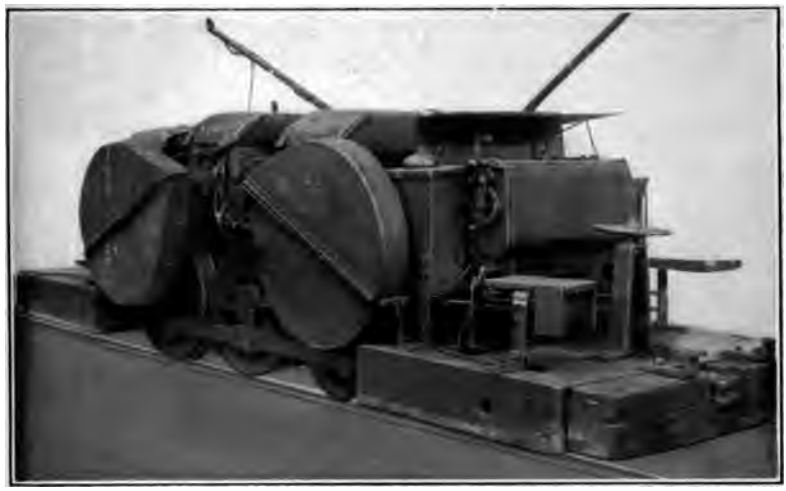


FIG. 1 [EATON]

FIG. 2 [EATON]

FIG 3 [EATON]

FIG. 4 [EATON]

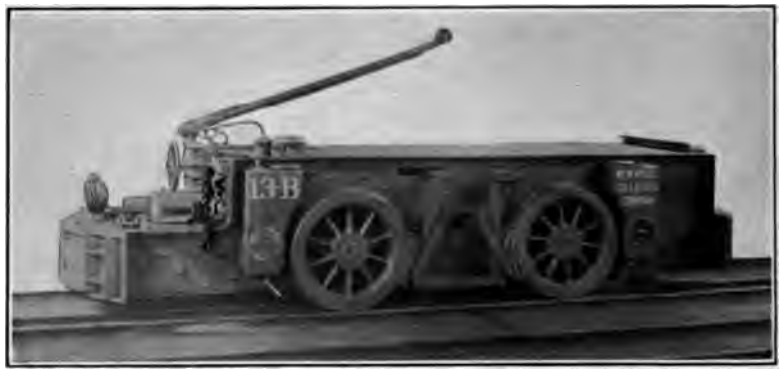


FIG. 5 [EATON]

FIG. 6 [EATON]

FIG. 10 [EATON]

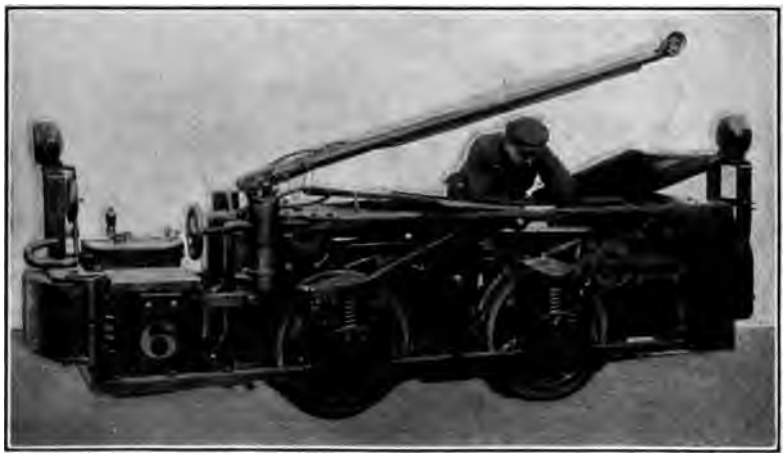


FIG. 11 [EATON]

FIG. 12 [EATON]

ment of locomotive framing. The causes for gradual changing of ideas were fundamentally two. First, the entry of locomotives into gathering service, and the consequent necessity for lighter locomotives to negotiate flimsy, rough track in rooms, and second, the demand for greater strength to withstand the rough and tumble gathering service, and increasingly severe main haulage service.

Sections were trimmed smaller and more care was taken to put the metal where it would do the most good. It was the nrealized that it would be an excellent plan to produce locomotives which, if damaged in a wreck, could be repaired in the mine blacksmith's shop. Fig. 5 shows a locomotive with plate and angle framing, which meets this requirement to quite a degree. Such a machine is far lighter for a given strength than a cast iron frame machine., There is, however, a rather definite maximum weight limit beyond which it proved to be poor economy to push this type of machine. Larger machines when laid out with plate and angle construction proved to have such high weight economy that it was necessary to ballast them to give the weight required for adhesion, and when laid out with cast iron members the strength was sufficient for all ordinary requirements.

A step further with this general type of construction is shown in Fig. 6, where bent flanges replace the angles shown in Fig. 5.

In case of a collision with these plate steel frame locomotives, a certain amount of bending and buckling may occur, but the framing can be straightened up in the blacksmith's shop, and the locomotive returned to service with a minimum of delay.

Another type of frame which is extremely substantial and which lends itself to heavier locomotives consists of a single heavy rolled steel plate cut out to the desired shape. This type of frame is practically unbreakable, and it has been used quite extensively.

A very interesting combination of cast iron and structural steel frame is shown in Fig. 7. Several such locomotives have been turned out and have given good service. In case of a bad crumpling of the frame, the operator can secure a commercial angle and bar or he can carry a length of each in stock and can make quick repairs on the ground.

If the end casting breaks he can secure a new one and make replacement himself without an extensive disassembly of his machine. He can also lengthen the locomotive wheel base, should he so desire.

The next step was the cast steel bar frame shown in Fig. 2. This frame has been thoroughly demonstrated in steam locomotives and in electric locomotives for main trunk line railways. Its main advantages have been summarized under Fig. 2. Figs. 8, 9, 10, and 11 show the convenience with which such fundamental parts as brake shoes, armature bearings, oil wells, commutators, etc., can be inspected and maintained. The motor is open to air circulation and will therefore perform a given all-day service with less temperature rise than when operating in a more nearly enclosed space. For purposes of quick production the cast steel bar frame was at first considered inadaptable. If a large, special steel casting must be made for each new locomotive, quick production is difficult. Fig. 12 shows a locomotive with cast steel bar frame in which two pedestal openings at the left-hand end are cast in embryo, as it were. By machining out the lower chord of the frame in the wake of the proper pedestal opening, the same casting can be used for either inside or tandem-hung motors. This casting is also designed to suit either inside or outside frames. These castings can then be carried in stock in the more popular sizes of locomotive and comparatively quick shipments are possible. This type of frame lends itself to a certain amount of repair at the mine. It is, however, based more particularly on the principle of making a frame that will resist damage to a greater degree than plate and angle construction, at some sacrifice of the ease of making permanent local repairs. A bent frame can be heated and straightened at the mine forge. The chance of a frame breaking is very remote, in fact, out of the large number of locomotives with this type of frame produced to date by one large concern, only one case of cracked frame has been reported. This occurred in a severe collision, and the frame was replaced.

In steam locomotive practise, the great length of the cast steel frames, and the heavy strains incidental to high speed and high power, cause considerable frame breakage. Welding by either the thermit or the electric process proves very satisfactory, and could be employed in the event of breakage in mine service. The thermit process would be the most practical, especially in small operations, on account of the simplicity of the necessary equipment.

To meet the demand for the maximum drawbar pull with a minimum of weight, a variety of types of locomotives has been introduced. The first locomotive illustrated in Fig. 1 shows one

effective method, namely, the coupling of the axles by means of side rods. In this machine, rod drive was adopted as a ready means of applying standard industrial motors rather than for the purpose of securing maximum drawbar pull.

Fig. 13 shows a locomotive equipped with a single motor geared to one axle and rod connected to the other, to secure the total weight for adhesion. In this type of machine, the advantage of simplicity and smaller number of parts is secured with the sacrifice of the advantage of the series parallel connection.

The same general result is secured by connecting the axles of a single-motor locomotive by one or by two chain and sprocket systems, instead of by side rods.

Another method consists of gearing a single motor directly to both axles. The motor may have its shaft parallel with the axles with double reduction spur gearing, as shown in diagram

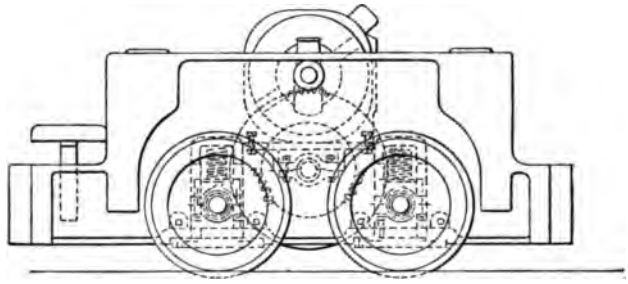


FIG. 14

in Fig. 14, or the motor shaft may be longitudinal, with bevel gearing.

In all of these arrangements, the reduced complication of the single motor is more or less offset by the great complexity of the transmission system.

In the early locomotives, cast iron wheels with chilled treads were universal. The introduction of steel-tired wheels was first made to secure a longer wheel life. These wheels, however, also contributed the advantage of greater adhesion, particularly with sand. The ultimate possibility in drawbar pull with a given weight of locomotive is of course the rack rail machine.

In the pursuit of greater capacity on a given gage, or to suit a fixed cross-section of entry, the next logical step after maximum drawbar pull is secured from two axles, is, in mine service, as in trunk line locomotives, the addition of more axles. The history of the mine locomotive, however, is different from the trunk

line machine in that the first step which was broadly applied in the mine locomotive was from two axles to four axles and later, in a few cases, to three axles. This of course was due to the almost universal existence of sharp curves that strictly limited the available wheel base. Fig. 15 shows a tandem locomotive. This particular machine is not necessarily permanently coupled. It is equipped with a single controller on the left-hand half, which handles all four motors. Flexibility of operation is secured by equipping the right-hand half with a controller capable of handling two motors only.

The locomotives can thus be operated as single or double units according to the exigencies of the service. Also, in case of injury to one half, a minimum of reduction of mine output occurs.

When the main entry is laid out with liberal curves, it is possible to have three axles arranged in a single long rigid wheel base. Fig. 16 shows a locomotive of this class.

In developing low coal veins it becomes important to keep down the over-all height of the locomotive to an absolute minimum. Fig. 17 shows a locomotive in which the flange of the wheel is the highest part of the machine. These low locomotives are of course particularly desirable where bad roof conditions make it inadvisable to blast down the roof to secure added head-room. Such machines are also advantageous in gathering from low rooms, as lack of head-room makes it difficult for men to push out the cars. This brings up the general subject of gathering locomotives.

At first the gathering locomotive was simply a small edition of the main haulage machine. Such a locomotive of course requires in the rooms steel rails more or less effectually bonded, and a trolley wire.

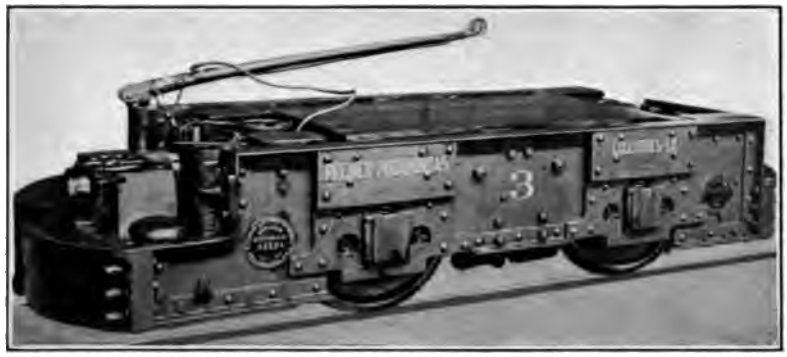
For various reasons it is often undesirable to introduce these features into the rooms. The cause may be danger to the miners, gaseous condition of the mine, or expense. These objectionable features are partially overcome by equipping the locomotive with a reel carrying a single-conductor cable, as shown in Fig. 18, and running steel rails, but no trolley wire into the rooms. A still further elimination is secured by fitting the reel with a double-conductor cable, when unbonded steel rails, or wooden rails, can be employed. With wooden rails, the locomotive weight is practically limited to about five tons.

Another method of eliminating the undesirable features is the application of the storage battery to the gathering locomotive. This is a comparatively recent development, but with the modern storage battery with its ability to resist mechanical shocks, the

FIG. 13 [EATON]

FIG. 15 [EATON]

FIG. 16 [EATON]



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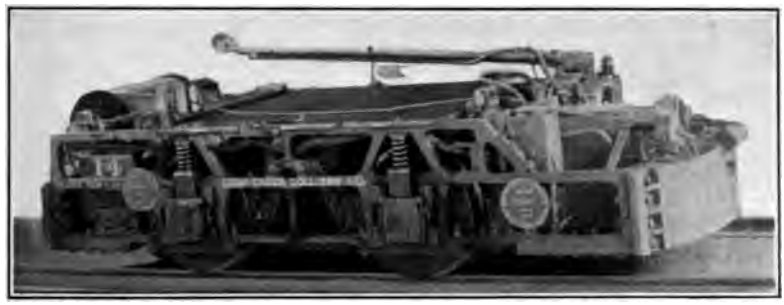

FIG. 18 [EATON]

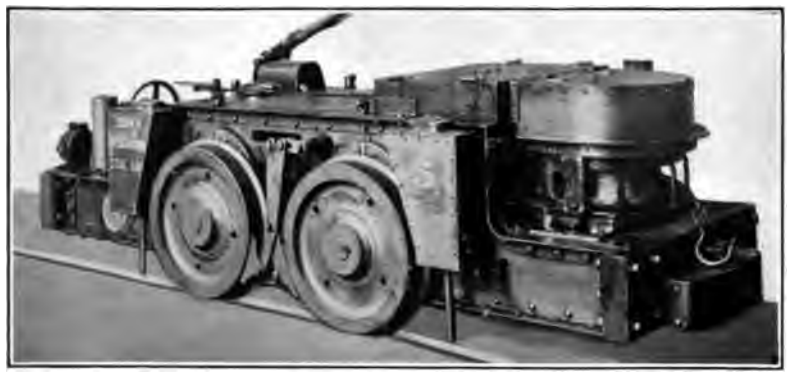

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FIG. 20

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FIG 21

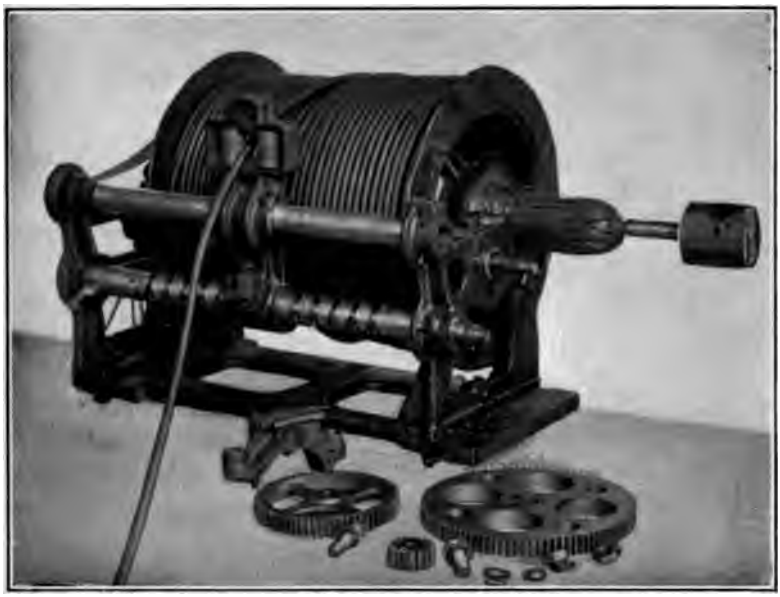

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FIG. 22

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FIG. 23

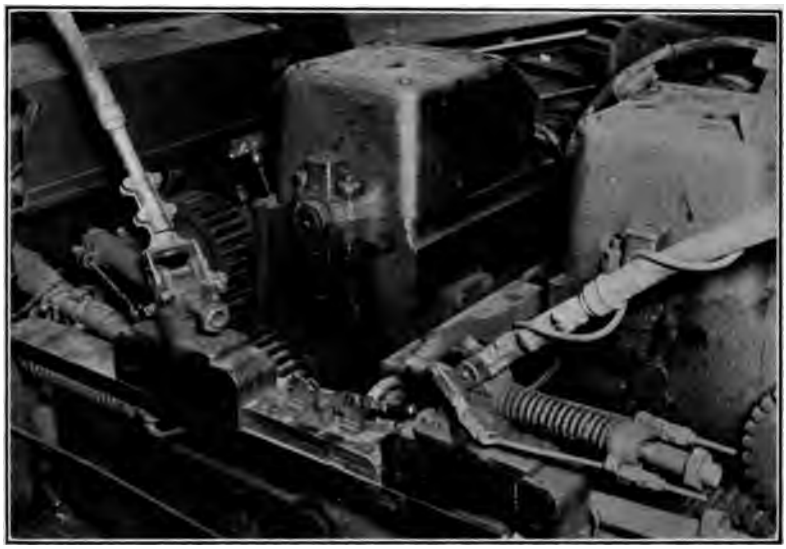

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FIG. 24

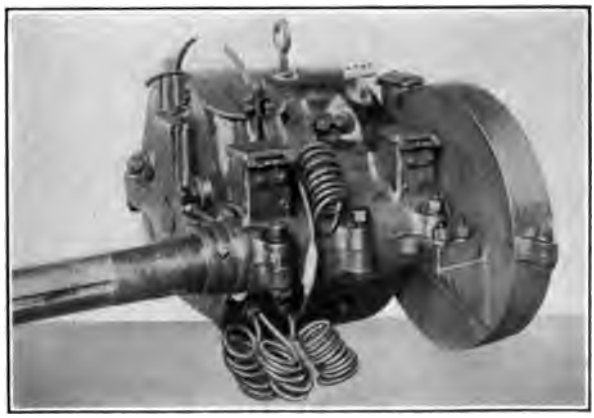

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FIG. 25

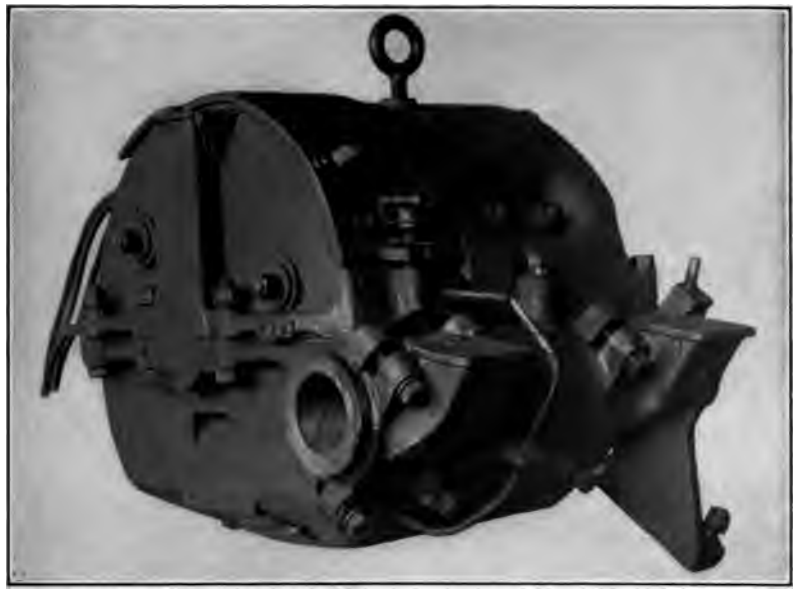

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FIG. 26

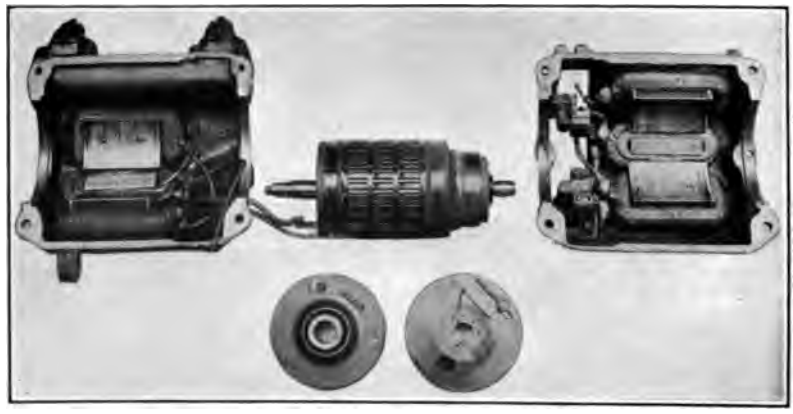

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FIG. 27

locomotives of this class have given promise of being thoroughly practical.

The locomotive can gather from the rooms without entering them if a traction reel or crab is installed on the locomotive, as shown in Fig. 19. This type of locomotive can haul cars from the rooms, but of course cannot deliver empties to the face.

A comparatively small number of locomotives have been produced on which both types of reel are applied.

The earliest form of cable reel was driven from one axle by a chain. Two general types are in use, one with its axis vertical, as shown in Fig. 20, and the other with its axis horizontal as in Fig. 18. Both have an inherent weakness. When the rooms dip to the entry, it is necessary to brake the locomotive when bringing the car out. If the wheels from which the reel is driven slip on the rail, the cable slackens, and is liable to be run over and cut in two. To overcome this, two types of reel have been produced, one with long clock springs, which are wound up on entering and which unwind and recover the cable on the return. A later general type is driven by an independent motor which is connected across the line through a resistance and is in effect an electrical spring.

There are here as in the case of the axle-driven reel the vertical axis type and the horizontal axis type as in Fig. 21. In the latter type the armature is inside the reel. Fig. 22 shows the method of removing an armature. The resistance used with this type of reel is the heater type of resistance where the resisting element is mica-insulated and hermetically sealed in a steel tube.

A traction reel with bevel gear drive is shown in Fig. 23 in rather more detail than in Fig. 19. The reel can haul through an angle of slightly over 180 deg., or over 90 deg. from the track on either side.

As locomotive development has been perfected, attention has focussed more and more on facility in overhauling. For example, in the early types of locomotive with frames outside of the wheels, it was necessary in order to remove a journal box, to drop the axle or jack the locomotive till the box was entirely clear of the side frames. Fig. 4 showed a locomotive where this is necessary. Various designs were later adopted where this is avoided. Fig. 8 shows another solution where the pedestal gibbs are interrupted and when the locomotive is jacked sufficiently to slack the spring the segmental pedestals are out of mesh and the box will slide out freely. This feature is representative of many details that have been similarly improved.

As has been previously stated, the earliest locomotives were electrically equipped with apparatus designed for other types of service. As the electrification of mines gained headway, it became evident that the severity of the service demanded more sturdy equipment. The motors received the first attention. Some of the leading types will be reviewed. The motor used on the locomotive shown in Fig. 1 was a bipolar type and is shown in Fig. 24. Fig. 25 shows a motor split through the axle. A very large number of locomotives are running with motors of this class. The overhauling of such motors and particularly the renewal of axle bearings is more difficult than with many of the later designs. This motor in common with all the earlier types is arranged for grease-lubrication of both axle and armature bearings. Such bearings in general require the addition of lubricant at least once a day, and sometimes much oftener. With proper attention, however, they have given very good results.

Fig. 26 shows a motor with independent axle caps. Both axle caps and suspension attach entirely to the lower half of the frame. This permits of ready overhauling of the motor. The excellence of this general arrangement was first proved in city and interurban railway service and it proved equally successful in mine service and has been widely adopted.

The great advantage of oil and waste lubrication over the earlier grease lubrication was proved in the street railway motor. Its wide success in this field led to its introduction into mine service. Fig. 27 shows a mine motor so equipped.

This experiment was entirely successful and was also widely adopted. This form of lubrication in combination with high-grade bronze bearings is in fact so thoroughly successful that it is still considered by some locomotive builders to be the best all-around solution. In one complete line of motors that has been on the market for some years, there has been no case reported where this type of bearing has failed. Other builders in discarding grease bearings have standardized on various well-known types of ball or roller bearings. It is to be hoped that the comparative merits of the two general types of sleeve versus frictionless bearings will be brought out in the discussion.

In addition to the mechanical improvements of the motor, the electrical designs have made a great advance. The most notable feature has been the addition of commutating poles. This is of particular advantage in mine service, where there is little or no coasting, so that there is no chance to polish the com-

mutator. In such service, the best of commutation is essential. Fig. 27 shows a typical arrangement of motors with commutating poles.

The motors of today are designed with particular reference to securing a high continuous rating, since this means the greatest tonnage delivered at the tipple.

In the early days the resistance gave a great deal of trouble. Various forms of cell and ribbon type resistance were employed. These were gradually superseded by grid resistance, till today this is the accepted standard. The first introduction of grid resistance, however, was by no means the solution, and both

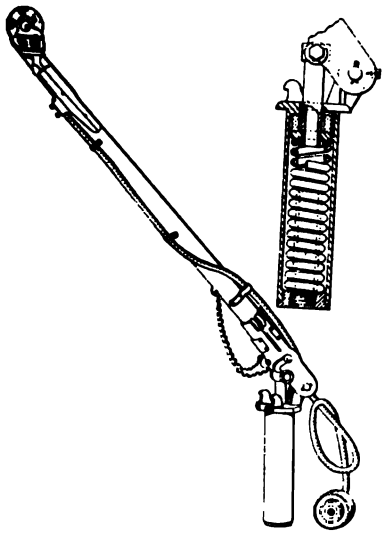

FIG. 28

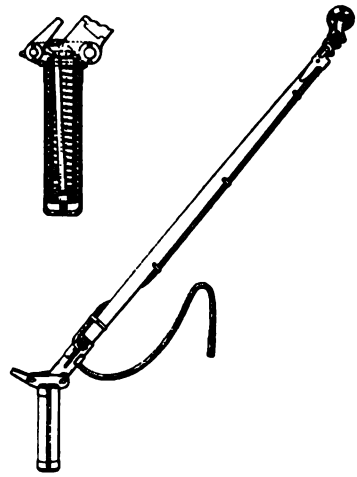

FIG. 29

manufacturers and operators could fill an evening with harrowing reminiscences of grid resistance grief.

The first controllers applied to mine locomotives were series-parallel or type K controllers. The size and particularly the height of this type caused the early adoption of the rheostatic or type R controllers. The early R controllers were without means for series-paralleling the motors. The reverse drum was later modified to include a series-parallel switch. The next improvement was the incorporation of means to make it more difficult to buck the motors. Magnetic blowouts have been used on all these controllers.

Fig. 28 shows an early form of trolley which was widely used. This was later superseded by the trolley shown in Fig. 29. The

principal changes which were made in this latter trolley were for smoothing out the contact pressure curve; that is, a proportioning of the operating mechanism details, so that within the working range the pressure on the trolley wire would remain approximately constant, regardless of the height of the trolley.

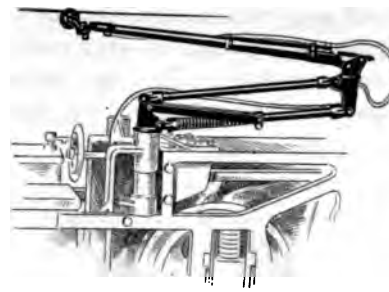

FIG. 30

The trolley was also arranged so that pressure of the wheel on the wire could be adjusted without any overhauling of the trolley.

Fig. 30 shows a form of trolley specially adapted for use with high cars where the other forms of trolley strike the car or the

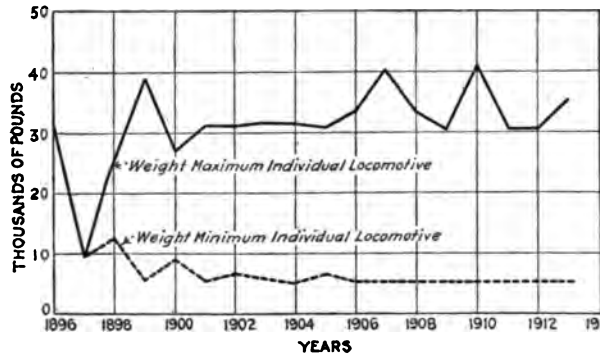

FIG. 31

coal in the car. This trolley is also adapted for use in the iron mines.

Many other detail developments could be pointed out, but it seems preferable for these to be brought out in the discussion.

The following curves show roughly the trend of the times in a few lines of development. These curves are based entirely upon

the locomotives built by one manufacturer, but it is believed that they are fairly representative.

The curves in Fig. 31 show the maximum and minimum weight

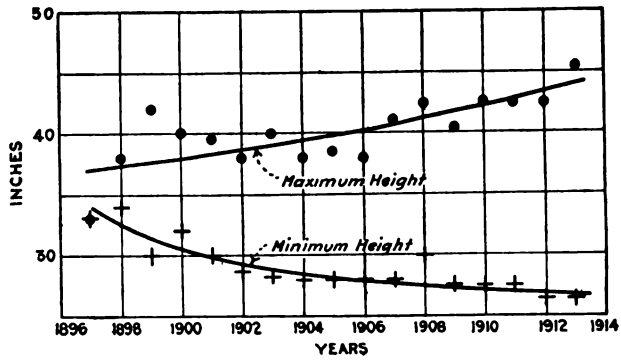

FIG. 32

in pounds for locomotives shipped each year from 1896 to 1913 inclusive.

In connection with the maximum curve, it is interesting to note that the first mine locomotive ever shipped by this particular builder is the heaviest it has ever put out. This was a

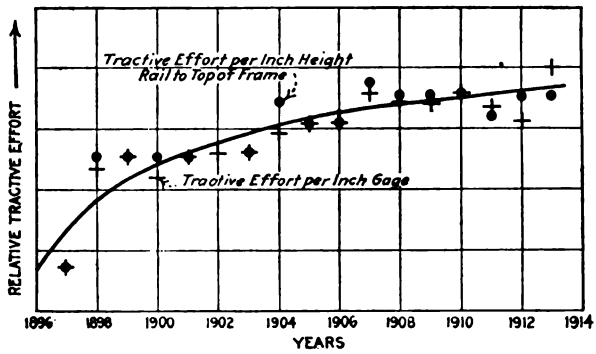

FIG. 33

three-axle machine, and is therefore not included in this curve. There is no pronounced tendency of the maximum curve. In 1899 a two-axle locomotive was built, weighing approximately 40,000 lb., (18,143.7 kg.) and several of about the same weight have been built since that time. This limit has held for so long

in coal mine service for this type of locomotive, that it seems to be pretty definitely settled.

The minimum weight locomotive has had less sharp variations. This is natural because far more locomotives of this size are required, and many are put in service every year. The minimum weight locomotive also established itself in 1899. It will be noted that improved frame constructions have in the smallest locomotives been capitalized in the shape of increased factor of safety and more powerful equipment instead of in decreased weight.

The curves in Fig. 32 show the maximum and minimum height from rail to top of frame, for each year. The maximum height curve shows a rather definite climbing tendency. If the one high spot in 1899 were absent, this tendency would be more definitely pronounced. It looks, however, logical to expect higher locomotives.

The minimum height curve is getting very close to the horizontal. It seems probable that no radical decrease is to be expected, as there is great inherent difficulty in operating these exceedingly low machines.

The curve in Fig. 33 shows in a striking manner how power has been crowded into a continually smaller space. The term power is used advisedly although the curve is based upon tractive effort, because the speeds involved in the years vary very little.

The general tendency of this curve would seem to justify the expectation of a gradual increase in tractive effort, relative to gage, while the plotted points if faired up for tractive effort relative to height, offer little hope of radical improvement with two-axle locomotives. Inherently, it is possible to double the height of the curve by using tandem locomotives. An attempt was made to show actual results with tandem machines, but so few have been made that the plotted results are jagged and show no tendency that can be profitably analyzed.

This brief discussion of the curves is offered only for what it is worth and not as a prophecy.

DISCUSSION ON "THE DEVELOPMENT OF THE ELECTRIC MINE LOCOMOTIVE" (EATON), PITTSBURGH, PA., APRIL 10, 1914.

W. W. Miller: Referring to Mr. Eaton's paper, it may be of interest to note that a mine locomotive of 14,000 lb. weight with a single motor chain drive was built in 1886, and installed in the anthracite field. This locomotive was in daily operation until 1909, and although preserved since then for its associations and historical interest, it is still used in the mines whenever required by emergencies.

While the cast steel bar frame mentioned may permit a design of less weight to meet stresses applied in certain assumed directions, it is believed that the rolled plate frame is better adapted to withstand the abnormal and unforeseen stresses due to derailments, collisions, etc. Moreover, in all of the more usual sizes, *i.e.*,five to six tons for gathering, and ten tons or heavier for main entry service, weight is fixed by drawbar pull requirements and not by mechanical design, or, in other words, it is necessary to "ballast" the locomotive.

With the rolled plate frame, this ballasting is accomplished by increasing the power section, thereby maintaining the weight distribution over the axles and making the locomotive power so much the stronger and more stable. Ballasting by means of heavy cast iron bumpers, as is sometimes resorted to with the cast steel bar frame, has the disadvantage of causing unnecessary power stresses and giving a strong tendency to tilt, unless the wheel base is of more than the usual length. Also the integrity of metal in the rolled plate frame is believed to be superior to the best of castings. It might be well to state that some of the rolled steel frames I have seen are from five to six inches thick, and ballasted by means of heavy cast iron.

Because of limited clearances in haulage ways, it is desirable in the interests of safety first that a smooth unbroken surface, which cannot catch clothes or tools, and which does not allow trip riders or miners to ride on the side at the risk of life, should be presented by a passing locomotive. The rolled plate frame with all bolt heads, etc., countersunk fulfils this condition admirably.

While in some designs the openings of the cast steel bar frame may be utilized as hand holes, all main adjustments must still be made from above, consequently it would seem that the lessened protection to the equipment has not brought with it a compensating increase in accessibility.

The expression "frictionless" as applied to bearings of the ball type in contradistinction to the usual sleeve type, does not emphasize their most important characteristic. While experimental tests seem to indicate considerably better starting torque due to their use, and it would seem reasonable that their lower friction coefficient would save something in full speed operation, their most important quality is in maintaining the absolute integrity of the motor air gap.

Few people realize what a large proportion of armature and commutator troubles have their inception in bearing wear. With ball bearings in a properly designed housing, so that they are dust protected, and with even fair attention to lubrication, the wear is entirely negligible. Recent inspection of such bearings after 20,000 miles of locomotive operation, showed wear that could be measured only in the ten-thousandths of an inch.

C. W. Beers: I am very much interested in Mr. Eaton's paper on electric mine locomotives, and as they are important factors in the production of coal, I would like to refer to some of the features which I consider to be essential to good locomotives.

As to the locomotive cover, it was originally made of wood, resting snugly on offsets in the side frames. In time these wooden covers would swell and cause trouble. A scheme that I have adopted with apparent benefit is similar to the cover shown in Fig. 2 of Mr. Eaton's paper, except that each cover piece extends over the side frames about two inches on each side. The cover plates are so supported on circular supports that they are about one and one-half inches above the side covers. This is a very good plan, as it gives free vent to the heat that is generated and permits the locomotive to cool more quickly.

I have found that the ordinary cover on the main journal bearings is not a satisfactory device for keeping out the grit, sand, etc., from the brasses, as in time this lid will not close properly, and hence the wash and sand from the locomotive will find an entrance. This causes a rapid wear of the brasses, and a tapering wear on the axle. To overcome this, I have adopted the plan of having this cover lid arranged to bolt fast to the bearing, and so far, I have found it to work out satisfactorily.

The old method of running the cables from the controller to the rheostat and motor was very unsatisfactory, as the cables would bunch on top of the motor and the vibration would damage the insulation. To overcome this feature, I have arranged on our later locomotives that cables coming from the controller should be placed in a built-up metal box, fastened to the inside top edge of the locomotive side frame, and from this main cable box the various cables would run straight out to the motor and rheostat. This makes a very satisfactory job, and keeps the top of the motors clear, as well as reducing cable troubles.

The old method of attaching cables to the rheostat by means of set screws was responsible for much trouble, as the screws would work loose or cut the cable and cause damage. We have overcome this trouble in our later type by using a clamping connection.

The brake reach rods in some of the locomotives pass over the top of one of the motors. This caused much annoyance when repairs were in order, as it meant dismantling part of the brake rigging. By having the reach rods pass along the side of the motor, this annoyance has been eliminated.

The arrangement of the foot pan is usually bad, because it

is usually bolted to the bottom of the side frame. This is shown in Figs. 8, 9, 10, 11 and 12 of Mr. Eaton's paper. Hence, when the locomotive rides over an obstruction, these bolts are liable to be torn out and the foot pan drops and may break the operator's legs. By fastening this foot pan to the iron ledges attached to the inside of the side frame, this danger is removed.

The ordinary covered and braided cables that are used for connecting the various parts of the locomotive to the equipment are not usually very successful, as the braiding soon separates and becomes fuzzy and in damp mines this is rather annoying. I think that cambric cables, with a hard, wear-resisting braid of good quality, could be used to advantage.

In regard to circuit breakers; I prefer a circuit breaker if it is a good one. I do not believe, however, that the development of the locomotive circuit breaker has kept pace with the other parts of the equipment, and the circuit breakers furnished today on some makes of locomotives are very poor devices. The breaker should be stout to resist bumps, etc., it should be waterproof, and so arranged that it cannot be kept from operating by the use of the foot, sticks, wires, etc.

The development of the mine locomotive is a problem that cannot be put up entirely to the designing engineer. Rather should the experiment be brought about by the operating man, and by careful watching, many defects can be remedied, as I have found that the desiging engineer is usually very glad to co-operate with the operator. Many of these points which I have mentioned are the result of my observation and of conferences with these men.

The maintenance of the mine locomotive is largely a question of looking after details. Generally, the manufacturing companies handle the question in a very satisfactory manner, but it is usually the little things that happen in every-day operation that they are somewhat unprepared for, and it is here that the operating man could be of use.

For some years past I have endeavored to keep a record of locomotive costs, the costs to cover armature repairs, field coils, armature bearings, journal brasses, wheels, axles, gears and pinions, also brake shoes, controllers, rheostats, trolley poles, oil, grease, crabs, reels, sand, brushes, journal springs, etc. By getting these various costs for each colliery, curves can be plotted that will give a graphic comparison of the costs for each place, and by means of personal knowledge of the conditions at each place, due to long experience, it is usually an easy matter to take any colliery and point out the proximate reasons and causes for the high costs.

For instance, high rheostat costs, combined with high journal spring costs, indicate bad tracks, cross-overs, etc., and high brush costs and high bearing cost usually mean high armature costs; or, again, high wheel costs usually follow the sand curve, etc.

A close study of such a set of curves will indicate very closely what part of the locomotive needs redesigning to better advantage, or what internal conditions need attention.

From curves plotted in this manner, it would seem that the costs of armatures, bearings and brushes were closely allied. An investigation showed that bad armatures were usually caused by bad bearings. Naturally, if the bearings were bad the armature would not run true, and this caused commutator troubles which put the finishing touches to the armatures.

During the past year I have had thirty-nine armatures sent to the repair shop with old bearings attached, and instructions were forwarded to the repair department that as soon as an armature was received, its shaft should be trued up and the bearings babbitted to suit. Out of thirty-nine armatures thus sent out, only one was sent back for repairs. This appears to me to be investigation in the right direction, and also points out the fact that armature bearings can be further improved.

The brushes also came in for their share of experiment, and we find that massive pigtails are a distinct advantage. The pigtails ordinarily furnished are not particularly good. The pigtail should be so large that it shunts practically all the current from the brush holder to terminal, and thus relieves the brush holder of its electrical function as a conductor.

We are now conducting experiments with impregnated field coils, but up to the present time have nothing definite to report.

Referring again to locomotive costs, it may interest some to know the relative percentage of these costs. My experience indicates the following:

Armatures and bearings	16.60	per cent
Field coils	3.10	" "
Rear axle bearings	1.43	" "
Journal brasses	1.12	" "
Wheels and axles	14.90	" "
Pinions	0.75	" "
Gears	1.73	" "
Brake shoes	1.15	" "
Controllers	2.10	" "
Rheostats	1.24	" "
Trolley repairs	3.35	" "
Oil	1.29	" "
Grease	0.51	" "
Sand	6.13	" "
Brushes	0.72	" "
Journal springs	0.50	" "
Reels and crabs	3.00	" "
Miscellaneous material	16.46	" "
Labor	23.80	" "

It should be noted that this cost also includes warehouse material that has been purchased and charged out, although no use has been made of it up to the present time.

Probably the most frequent cause of locomotive trouble is due to bad bearings. When buying a new locomotive, we find that it will run from eight to fourteen months without much repair, after which time it is usually necessary to replace the wheels, and from this time on the repair costs are usually high.

In an endeavor to find out the cause of such increase, I have reasoned the matter out in this way: When new, the bearings and all parts have a good clean fit. After a time the use of sand is introduced, and this simply accelerates the wear, and soon the bearings are no longer good and considerable play is in evidence. Just about this time the gear and pinion show considerable wear, and begin to pound. This has a very bad effect on the armature and produces a bad effect on the commutation, and the armature is no longer central. Consequently the brushes get hot, the commutator blackens and the armature is then in line for repairs. After watching this performance a good many times, I have come to the conclusion that, since it is impossible to stop the use of sand, some form of bearing, both for rear axle and main journal, should be designed that is sand-proof. The armature bearings, of course, should be sand-proof, and in addition should be hard enough to stand the pounding of the gears, and both the sleeve type and ball bearing type appear to be improvements in the right direction.

During the past, our experience with gear wheels indicated that there was much to be desired concerning them, and from data that we have I find that gear costs follow closely the wheel and axle costs, and to my mind that indicates quick wear of gears and pinions and hence rapid wear of armature bearings due to the pounding of the gears. We are now trying out some extra hard gears and pinions, and expect to get better results.

Probably one reason for excessive gear and pinion wear is due to the fact that gear cases are not constructed to keep out dirt and grit. These find their way into the gear case grease and, of course, cause rapid wear. It occurs to me to ask if any one present has operated his locomotives without the lower half of the gear case.

In speaking of the reel or crab, Mr. Eaton says that locomotives equipped with this device cannot deliver empty cars to the face. This is not my experience, as I find in pitch regions that the crab can do this very well by means of a dead rope and a bull-wheel in the face, or by carrying the rope to the face. On the same page Mr. Eaton describes a clock spring reel. The idea is good, but it is very expensive to maintain, and I do not recommend its use.

Regarding the use of ball bearings, we have a few in use. They are good, and better than the babbitted shell. They are rather expensive to renew, but they do keep the armature in good shape. My experience has not extended over a sufficiently long period of time to state whether or not they are

better than the sleeve type, but almost any type is preferable to the babbitted shell, as these are usually soft and are easily pounded.

On account of the poor tracks which are encountered in the mine, it appears to me that grid resistance should be more flexible. A broken grid is usually responsible for ultimate armature and controller trouble.

Carl J. E. Waxbom: With reference to the design of electric mine locomotives, we believe that some stress should be placed upon the "safety first" idea, and we found it absolutely necessary to adopt a type of frame which was unbreakable, and such a type of frame is found in the rolled plate or slab frame construction. We found that the use of cast frames, whether of steel or iron, has always resulted in some flaws being found in the castings, and this experience, I believe, will be borne out by everybody. Therefore, I think that the rolled plate frame has overcome that objection.

With reference to ball bearings versus sleeve type bearings, I think that the ball bearings have a decided advantage, inasmuch as they lessen the cost of operation and upkeep of the locomotive, particularly that of the armature. This cost, I have found, in some cases amounts to as high as 80 per cent of the total cost of the upkeep. We applied some ball bearings some six years ago, and they are still running without any wear. I have also found users of mine locomotives who have expended, for a year's service of 16 locomotives, only $10 for the cost of lubrication. These locomotives, as I recollect, have been in service for over two years, and after a periodical examination of the ball bearings there was no perceptible wear on them.

The most important point in our opinion is that in the design of ball bearing housings care should be taken so as to preclude any foreign material getting into them, and with that design I would say that the ball bearing, with proper lubrication, should last indefinitely, or just as long as any other part of the locomotive.

With reference to the frame construction, I believe that the rolled plate type of frame should be recommended, even in case of the largest type of mine locomotives. I think that safety should be the first consideration in the design of mine locomotives, and I think that it is entirely met by the plate type frame construction, which, as one speaker stated, runs up to as high as six inches in thickness.

Graham Bright: I do not believe that the illustrations show nearly all of the advantages that are obtained in the open steel bar type of frame. The question has just been brought up in regard to the safety of this type of frame, in that men are liable to jump on the locomotive, and may slip and have their toes cut off. I have talked to several mine operators who are using this type of locomotive, in regard to this point, and they seem to think, while it might possibly occur in some mines, there are

probably only one or two openings where this could possibly happen, and they were willing if absolutely necessary to close those openings up with small plates and get the advantage of the other openings for inspection and ventilation.

There is no doubt in the case of the box type frame that, due to the heat losses of the motors and resistances, the temperature must get pretty high inside the box, there being practically no ventilation, and since the capacity of the locomotive depends on the continuous rating of the motors, (not the hourly rating,) for all day's service, there is no doubt that this continuous rating must be considerably increased by the ventilation obtained by the open steel bar frame.

Mr. Eaton states that with the single motor and side rod, you are not able to obtain a series-parallel combination of the motors. I mentioned yesterday in discussing Mr. Reed's paper that I thought this was more fancied than real, because in most cases you will find the motorman will not use the series combination on the controller. In the parallel position it gives a little easier start and he does not have to worry about changing the position of the reverse lever if he wants higher speed, and the result is that he seldom uses the series position. Unless we can obtain a series-parallel type, like a railway controller, that is low enough to be used for gathering service, I do not think there is much in the series-parallel combination, from a power economy standpoint.

Mr. Eaton calls the ball bearings "frictionless" bearings. Some tests have been made on a motor, with both ball bearings and with the sleeve type of bearings, in order to determine the difference. At very low speeds there is no question that the ball bearing has considerably less friction, but at medium and high speeds the difference is scarcely noticeable. In fact, some tests show that more friction is obtained with the ball bearing than with the sleeve type of bearing. Unless a ball bearing is properly lubricated and protected from dust it will very quickly give trouble and when repairs are required they will prove very much more expensive than with the sleeve type.

When the first mine locomotives were brought out, the motors as a rule did not have sufficient capacity for the service to which they were put. The result was that the electrical repairs were very high. There seems to be lately a swinging toward the other direction, and many operators and some consulting engineers are insisting on capacities which are really far in excess of what is necessary to perform a given service. The result is that the electrical repairs go down, but, on the other hand, the mechanical repairs mount very rapidly. The reason why these mechanical repairs are not so evident is that when the electrical trouble takes place as a rule you have no warning until the trouble actually occurs, there being no indication of what is going to happen. In the case of mechanical repairs, they can always be foreseen far enough ahead to have

repairs made without delay to the service. The result is that these high mechanical repairs are really not made manifest, but I think you will find where a locomotive is very much "over-motored" that the low electrical repairs are brought about at the expense of high mechanical repairs.

F. L. Stone: There has been a great deal said about the increased ventilation and the beneficial effect of the open side locomotives as compared with the box frame. I would ask if any concrete tests have been made to substantiate the claim. Personally, I do not think it amounts to anything, because the box locomotive is open both top and bottom, and the fact that the sides are closed does not, I believe, make any material difference.

G. M. Eaton: While I have no definite comparative tests of mining locomotives with solid and bar frames in exact conditions of service, I would call attention to the fact that in testing a motor in the shop, if one inadvertently leaves the window open, perhaps ten feet away from the motor, on a day that is moderately cool, there is a very great difference in the results that are secured. Personally, I have no doubt that if the motor can run in free and open air, that is cool, it increases the capacity of the machine.

L. J. Ilsley: In regard to locomotives being "over-motored" or "under-motored," in my experience with several different types of locomotives, it seems that the average motorman is inclined to haul just about all the locomotive will haul; it is the same old question—if he had a mule that would pull three cars, he would attempt to pull four cars with it. If he could easily haul four cars with a locomotive, he would try to haul six cars. I have known of this problem being met by reducing the gear ratio, and by using heavier motors, so that the motorman can only haul a certain load, and, therefore, not overheat his armature and his field coils. This is harder on the wheels and the brake shoes, but I think, on the whole, it is a saving to the mine operator.

In regard to the cable reel which is operated by a motor, and reels out against the torque of the motor, I had experience with a different type of reel which works on the same principle, and this reel seems to work very well, except in cases where the trolley voltage is very poor. In the earlier types of locomotives there was a tendency in the controller design to make the terminal posts so small that one could get only a portion of the lead wires in them; one had to cut them down in assembling the wires. I am glad to see that in the later designs they have made ample room for putting in the leads both in the rheostats and in the controllers.

The question of the design of a mine locomotive should, in my opinion, receive special attention with regard to making repairs on the locomotive, for the average mine is not usually equipped with the best advantages and facilities for making

repairs. In the railroad shop you have your jacks and everything you require to handle the locomotive, but in the mine you may have a small pit out at some distant portion of the mine where you make your repairs, and, therefore, the locomotive should be designed to assist the repair man in every way, in changing armatures, wheels, and bearings. My experience in the maintenance of locomotives has shown that a great many of the troubles due to armature and field coil burn-outs are due to lack of inspection of the equipment.

W. W. Miller: I think the usual tests made on the motors Mr. Bright mentioned, with ball and sleeve bearings, are made with the same motor, with the same air gap. We have found, after considerable experiment, that you can use a much smaller air gap with a ball bearing motor. This means an increase in efficiency, with a resultant saving in kilowatts consumed. Recent tests on a considerable number of motors of various manufacturers indicated such material discrepancies in the service capacity of the motors having the same ordinary rating, that it would seem any slight advantage in external ventilation is entirely negligible, compared with the inherent electrical design and loss distribution of motors.

F. L. Stone: Mr. Eaton's reply to my question in regard to the actual heating tests on locomotives with open frames having been made, is only a partial answer. I agree with Mr. Eaton, that a motor would run cooler in a sealed room with one window open than it would with the window closed, but I question, if the motor was in a room with five windows and four of them open, whether the opening of the fifth window would make any material difference in the temperature rise of the motor.

W. A. Thomas: Some mention has been made as to the cost of production of various types of frames. Admittedly, a defective casting in the foundry does increase the cost of the cast steel frame. The structural shapes and plates we know, from market prices, can be purchased in a varying market from $1\frac{1}{4}$ to $1\frac{3}{4}$ cents per pound, and if any of you have had occasion to buy steel castings you found they cost quite a bit more per unit of weight.

Mr. Miller brought out an important point with reference to the use of ball bearings, that the easier starting is undoubtedly true with the ball bearing, because it is a point contact, and is, as Mr. Eaton brought out, somewhat frictionless. For that reason it is my judgment that there is a decided field for the ball bearing, especially in gathering work, which is made up of starting and stopping much of the time; but in the main haulage work, the use of ball bearings and that of the sleeve bearings has not had, relatively, enough trial to determine their respective merits, although one large operator, who tried locomotives of different design and of different manufacture, and all with the ball bearings, with the best design of housing obtainable, has stated that the advantages of the ball bearings which

they had hoped for, had not been obtained, and therefore in their later locomotives they were resorting to the oil-waste-packed sleeve bearing. That is only one case under one set of very severe conditions.

The contention that there is no wear in the ball bearing is theoretical. Experiments have shown that there is wear. Resorting to smaller air gaps to get more power out of a given weight has resulted in offsetting the main advantages of the ball bearing by the armature going down in the tail pieces on comparatively slight wear.

Another point which Mr. Beers brought out is an important one, with reference to the use of babbitted bearings, babbitt metal being subject to hammering from poor alignment of gears. This applies again because, as I think the last speaker brought out, you cannot get proper inspection of the equipment under various conditions of installation, and you get a very heavy hammering of the bearings due to the condition into which the gears wear. This, in some cases, is breaking the ball bearings and causing replacements, and in some cases the bearings will last only six months, being comparatively expensive to maintain.

It is extremely difficult, as Mr. Beers pointed out, to keep the sand out of any bearing. This is, perhaps, more important in the case of ball bearings than in the case of the sleeve bearing, because with the latter full of oil, the sand, if it gets into the bronze brushing, has a tendency to be carried out, whereas with the point contact there is a constant grinding, due to the fact that no attempt is made to keep a flow of oil through the bearings.

As regards the matter of safety, this appears to be largely theoretical, as is indicated by a recent order which the manufacturers have had for a bar type construction, in which order they have been requested to put in step plates in the end openings of the frame for the trip rider to get on.

The question of motor capacity should, perhaps be, qualified. Increased motor capacity obtained by speed has no advantage, because you have no greater tractive effort, relatively; and consequently—while the bare statement of power would appear advantageous—the speeds go beyond the practical limit, and the fact that you can only accelerate a certain train with a given tractive effort removes the advantage of the increased power. As a matter of fact, it is thought by some, and that thought has merit, that the question of the tractive effort in terms of the one-hour capacity of the motor, as laid down by the Standards Committee of the American Institute of Electrical Engineers, should be the prime consideration of the relation between the electrical capacity and the weight of mechanical equipment.

It is interesting to note in connection with the discussion of the gathering proposition, that as far as we are able to determine, and from my personal observation, the storage battery was the first type of gathering locomotive tried out. That

represented, of course, a battery of fifteen years ago, which was tried out at the Pocahontas Collieries at that time, and the electrician, after burning out several suits of clothes with acid, devised what was known as the "Wampus." The motors were hung outside in order to put the battery in the center. That left a relative short wheel base, with a clear field underneath the battery, so that when the battery was removed he took an old electrical wire reel, with wooden flanges on it, and put a shaft through it, and wound his cable up on this old reel. Then he mounted on the end of this shaft a large wooden disk, and on that end of the shaft he made an arrangement so that it would raise and lower the bearing support on the shaft, resting this disk on the wheels of the locomotive, and hoisting it off when he did not want to wind the cable. That was, so far as I know, the original gathering locomotive, and is interesting in connection with the general development of the locomotives.

I agree with one speaker in regard to the question of terminals. A great improvement has been made on the controller terminals, and I think further improvement can be made in increasing the size of the terminals and the method of attaching the same in the resistances. Mr. Beers made some statements on that particular point. Personally, I advocate either a terminal soldered on to the end of the cable, or else a sleeve soldered to the end of the cable.

As to the question of air-gap, I mentioned before that the relative dangers due to the bearing going down are modified to some extent in the ball-bearing motor by reducing the air gap, and unquestionably this removes, to a great extent, the claimed advantages of the integrity of the air gap, if you do not keep the same air gap as is used with the sleeve bearing.

G. H. Shapter: Mention has been made of the storage battery locomotive as a future possibility in overcoming certain difficulties encountered in gathering work. It is true that quite a number of such machines have been installed. Some of these have been more successful than others, and for the most part the few failures noted have not been due to the locomotives or batteries, but rather to conditions existing in certain mines, such as flimsy tracks, lack of sufficient ties or spikes to properly hold the weight of the locomotive and prevent the rails from spreading, curves improperly laid, etc.

In one instance I had occasion to note a track laid $\frac{3}{8}$ inch narrow, and as a natural result the locomotive was off track for an average of two hours per day. Now, to prove my point that conditions will be the obstacle that must be remedied, I will say that on the very next installation of a storage battery locomotive no trouble of the slightest character was experienced with derailment. The storage battery, in common with all other locomotives, must be provided with suitable rails in order to make their speed and increase the output.

Storage battery locomotives of a certain manufacturer are now operating successfully in coal mines, and range in capacity

from 500 lb. drawbar pull to 2400 lb., and speeds of 3½ to 5 miles per hour. The height varies from 27 in. to 46 in., and the width from gage plus 6 in. to gage plus 16 or 18 in., depending on whether inside or outside frames are used.

A careful study of the cost of operation, maintenance, repairs, power and attendance, etc., shows that a saving of from 30 to 35 per cent can be effected by the use of storage battery gathering locomotives as compared to mules. The calculations have been extended to a period of ten years and can be verified by actual results obtained in practise over a period of two years. The approximate estimated cost is four cents per ton-mile.

The segregated value of various items considered in the cost of operation of these storage battery locomotives is as follows:

	Alkaline			Lead		
Interest on investment....	3.7	per	cent	3.2	per	cent
Depreciation and renewals of battery.....	9.0	"	"	11.5	"	"
Depreciation of locomotive	6.5	"	"	11.5	"	"
Battery incidentals.....	0.8	"	"	0.85	"	"
Electrolyte renewals.....	1.0	"	"	0.00	"	"
Locomotive repairs, oil, etc.	2.0	"	"	2.15	"	"
Motorman and helper.....	65.0	"	"	70.00	"	"
Power for charging.....	11.5	"	"	5.40	"	"

The relative values of the two totals are in the proportion of 94 per cent to 100 per cent, showing a very close margin. Cost of power does not enter greatly into the case even when figured at two cents per kw-hr., and for most isolated plants this extra power may be obtained during periods of light load on the generator without extra costs.

Personally, I do not believe storage battery locomotives can be as yet considered on an equal efficiency basis with trolley locomotives, perhaps never will be, but most certainly they will prove better than mules or some form of cable devices.

Apprehension may be felt on the score of durability and strength of the battery. I have seen cases with both the acid and the alkaline battery where the battery has been compelled to deliver power for pulling the locomotive onto the track after a severe derailment, which they did without any apparent bad results. The heavy current drawn under such conditions can well be imagined when I say it was necessary to hold the current breaker in by the foot.

C. J. E. Waxbom: I want to call your attention to a point with reference to the ball bearings, which I believe has not been brought out as yet, and that is, there is no wear to take place on the armature shaft with the use of ball bearings, and I think that is an important point.

E. H. Martindale: It has been pointed out in the discussion on this paper that a great deal of trouble is encountered on electric mine locomotives due to worn bearings. It has also been

pointed out that a large percentage of the commutation troubles can be traced to the unequal air gaps caused by the low bearings. It is rather surprising to note in this connection that the slotting of commutators, that is, undercutting the mica from between the copper bars of commutators on electric mine locomotives, has not gained headway more rapidly. At the present time I do not think that more than 10 per cent of the electric mine locomotive motors are operated with slotted commutators, while on street and interurban motors probably 95 per cent of the commutators are slotted.

With the recent legislation in some districts compelling the mine owners to pay miners on the run-of-mine basis, it will be necessary for the operating department to cut down expenses wherever possible, if the mine owners are to continue to operate their mines profitably.

The slight saving in brush cost by the use of slotted commutators is of practically no consideration, the great reduction in cost being accomplished by the saving in commutation wear, reduction of flash-overs, and burned out armatures, and other commutation troubles. With an unslotted commutator on such severe service as the average electric mine locomotive motor, it is necessary to use a brush which has sufficient abrasive material to grind down high mica which is caused by the sparking which occurs under the severe conditions. This necessarily means a brush which is continually grinding the commutator, and the cost of a new commutator for a motor is usually more than the cost of the brushes that will be used on the motor for ten years.

The slotted commutators will permit the use of a high-conductivity, low-friction, non-abrasive brush, and the sparking which will be caused by unfavorable conditions, such as the worn bearings, will not have the serious effect upon the commutator and will show a very great reduction in maintenance charges. With slotted commutators, however, it will be necessary to have careful inspection at regular intervals to prevent coal dust, carbon dust or other foreign materials from collecting in the slots and causing short circuits.

N. W. Storer: There is one point brought out that I feel I am able to discuss, and that is in regard to the efficiency and ventilation of the motor. One gentlemen made the statement that ball bearings enabled the air gap to be greatly reduced in the motor—that is probably true, from a mechanical standpoint; and if it were desirable to use the minimum air gap possible with mechanical clearances, every motor would be built with that minimum air gap; that is, the minimum air gap for the particular type of bearing in use. Such is not the case, as every one knows. One motor may have one-eighth inch clearance, another one-quarter, or five-sixteenths, or three-eighths inch—it depends on the electrical characteristics that are to be obtained with the motor. It is not simply a matter of efficiency, either, in reducing air gaps. I think in a great many cases you increase the effi-

ciency of the machine by increasing the air gap. When a motor has an extremely small air gap, it is liable to have far more losses induced in the pole faces than it would have with a larger air gap and corresponding increase in the turns on the field, necessary to overcome the larger air gap. It is a case of having the air gap to get the commutating characteristics that you want, as a general rule, not simply to get sufficient space for the armature to turn in.

Now, in regard to ventilation; it is perfectly true, what Mr. Stone has said, that one window out of five makes little difference on the motor, but there is no question at all about the fact that a motor under a box, even though it may be wide open underneath and have small openings on top, is going to run a great deal hotter than one which has holes on the sides as well as the bottom and top. We know from experience that a railway equipment with a motor well surrounded by the truck, will run a great deal hotter than one which is more exposed, in fact, that a motor that is on the head end of a truck will run cooler than the one on the rear end of a truck. That has been tested out time and again. There may be 10 or 15 deg. difference in temperature between the motors on the same truck, depending on the location, whether leading or trailing.

G. M. Eaton: Mr. Beers asked a question about split versus solid gears. The split gear is at best only a makeshift, though often it seems unavoidable. If the operator has a small shop with no press, it is tremendously tempting to apply a split gear. It is easy to renew, and has to be renewed. As everybody who uses them knows, there are more or less troubles with the split gears. I say that, representing a company which sells a great many split gears. The company with which I am connected always recommends the use of solid gears, where possible.

With regard to the use of hard gears, they are surely coming in mine locomotive work. The use of the split gear has until recently made the use of a soft gear essential.

It is only recently that hardened split gears have been used, but they are now produced commercially by various manufacturers. They are expensive, but they make up for the increased cost by their long life.

Mr. Beers also called attention to the need of co-operation between the users and builders of electrical machinery. He struck the keynote of development. The more of such co-operation, the better.

" Safety first " is of vital importance. I regret that the discussion of this principle has been all from the side of the manufacturers, because although the manufacturers keep in the field, to a certain extent, they do not live day and night with the machines. The real proof of the safety of a given type of machine is its actual performance, and this record must come from the operator. Safety first must be observed, not only from the standpoint of the designer, but from the standpoint of the education of the men in the mine, that, as far as possible, the men

TEN-TON ROLLED-STEEL SIDE-FRAME LOCOMOTIVE [STONE]

must be made to realize where their lives are in danger. This is true, regardless of the apparatus used.

The storage battery locomotive which requires tracks better than those found by experience to be practicable and commercial, is doomed to failure. The storage battery locomotive must be adapted to existing conditions.

F. L. Stone (by letter): The question of open frame versus closed rolled steel plated I think is worthy of a little further discussion. In the first place, the mine locomotive of the future will be as indestructible as it is possible to make it. It must be able to withstand severe collisions and frequent derailments without injury. The open frame locomotive Mr. Eaton advises had its inception in the main line railway locomotive. This type of large locomotive is built for high speeds and is not designed to withstand collisions or derailments. There are many other stresses which they have to withstand, which do not necessarily enter into the design of the mine locomotive. Steel castings of the shape shown are at best of questionable strength, due to shrinkage stresses. I note Mr. Eaton says the frame can be repaired with comparative ease by either electric welding or by the thermit process. I do not know just how much significance to attach to this statement.

In regard to the stability and strength please contrast Figs. 8 and 18 with the rolled plate side frame shown herewith. I believe it is impossible to construct a locomotive that will withstand the severe conditions of mine service better than the rolled plate side frame locomotive. There are possibly some slight advantages to be gained by the open frame when it comes to renewing brake shoes, etc., but I do not believe Mr. Eaton would recommend the abandoning of the locomotive pit even though nothing but open side frame locomotives were installed in the mine.

The question of miners riding while standing on the frames should be further emphasized. Mr. Eaton advises that if they do ride they are liable to lose their toes, or be hurt against the mine rib. They will surely ride if there is a place for them to stand on and in all probability will get hurt.

In regard to the cooling due to the open frame it is not fair to contrast the mine locomotive with the high-speed railway locomotive, or to draw conclusions from one and apply them to the other. I have seen many schemes of ventilation fail, notwithstanding the fact that they look perfect on paper. When tests have been made, and evidently they have not as yet, I would be pleased to hear the results. Finally, a locomotive of a given drawbar pull must have a weight in proportion thereto. There cannot be a better place to put this weight than in the side frames. If it is placed outside the wheel-base the tendency is to make a "rocker", which is very liable to leave the track should there be any unevenness in the roadway. I have seen this rocking so bad that it was almost unsafe to run the locomotive.

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MINE SUBSTATIONS
Motor-Generator Sets vs. Synchronous Converters

BY WILL M. HOEN

ABSTRACT OF PAPER

The number of mines which use electrical power supplied by transmission lines carrying high-voltage alternating current is constantly increasing. Low-voltage direct current is usually required for underground work in all coal mines. These conditions require the installation of motor-generators or synchronous converters. The extent and location of the mine workings will determine the voltage of the direct-current supply. Improper application of the transforming apparatus may result in great variation of voltage in the direct-current network, with its attendant disadvantages.

The operating characteristics of the induction and synchronous motor-generator sets and synchronous converters are considered with regard to starting conditions, d-c. regulation and the effect on the a-c. transmission lines, a-c. voltage regulation, and power factor correction.

Mine conditions and the nature of the power supply will determine the type of transforming apparatus which will give the most efficient and satisfactory operating conditions. Each of the several types of apparatus has a field where the best results will be obtained.

DURING the past few years there has been a great increase in the number of mines, especially coal mines, using power supplied from the mining company's central power plant, or by central stations. Several central stations have recently built, and others have greatly extended their distribution, with the main object of serving mining districts. These conditions are making economical power possible for all kinds of mines. To provide economical transmission, this power is generally distributed at a voltage which requires transformation before it can be utilized in rotating machinery. Operating conditions at the average mine are such that direct current is required, and this requires the installation, as part of the mine equipment, of a motor-generator set, or a synchronous converter. The object of this paper is to show the adaptability and field of each type as applied to mine service.

In the small coal mine, where power for haulage service will

be a chief requirement, it is generally necessary, because of the mine location and layout, to feed power from the extreme end of the feeder system. Under these conditions, to avoid installing an excessive amount of copper and in order to maintain a reasonable voltage in the region of the maximum load, an increase in the terminal voltage of the d-c. generator becomes necessary with the increase in load.

However, when the mine workings become extensive, the low voltage generally used makes it desirable to feed into the feeder system at its load center, or even into two or more such places. This is sometimes accomplished by installing a substation underground, or in shallow mines, which are in favorable locations, on the surface, feeding the low-voltage current underground through boreholes. Under these conditions, an economical feeder system can be installed, so that the drop is low, and an increase of terminal voltage with an increase in load is not so necessary or desirable. As the mine system becomes larger, the amount and size of the apparatus will increase so that motors in constant load service, such as pumps and mining machines, will be distributed throughout the mine, to whose successful operation an excessive variation of voltage will be detrimental.

A direct-current motor, when subjected to an excessive increase in voltage, will have its shunt coils overheated, and its speed will increase, which will, with certain characteristic loads, overload the motor.

An excessive reduction in voltage will cause over-heating of the armature, reduced speed and reduced output. Series motors are generally used for intermittent service, and, as the torque is a function of the current, lower voltage will mean a greatly reduced speed and an increase in the time for any particular cycle of operation. This will invariably result in overheating of the motor windings.

Power for mine service is nearly always purchased on a unit basis and is easily and accurately measured. The actual cost of power is, therefore, accurately known, which is quite different from the former conditions, where each mine was usually served by an individual power plant where the actual cost of power was very indefinite. Due to the ease of ascertaining the actual cost, the mine operator is vitally interested in the over-all efficiency of the transforming apparatus.

The average mine is served with three-phase, 60-cycle power, at a voltage which is rarely higher than 11,000. Expert at-

tendance is not available or desirable. The first cost must be kept at a minimum, with the operating efficiency at a maximum. Direct current is required at a voltage generally under 300, but never exceeding 550. The selection of the proper apparatus lies between a motor-generator set, of the induction or synchronous type, and a synchronous converter. The starting characteristics of the last two types of machines have been very greatly improved, and the operation of the starting greatly simplified, within the last few years. The starting conditions of these machines in the order of their desirability follow:

1. Induction motor-generator.
2. Synchronous motor-generator.
3. Synchronous converter.

The induction and synchronous motor-generator sets consist of two machines, a motor and a generator, each electrically and magnetically independent. The generator can be given any reasonable characteristics, but standard practise is to flat-compound for 500 or 250 volts, or to over-compound not to exceed 10 per cent. The operating characteristics of the direct-current generator are understood by the average mine attendant, as its operation is similar to engine-driven generators with which he may be familiar.

The induction motor-generator set is exceedingly easy to start, but has the disadvantage of a small air gap and a lagging current characteristic, which causes the transmission line to carry an additional current above the required load current. This means an increase in the transmission line and power station generator capacity.

The synchronous motor-generator set of the present day is no more difficult to start than the induction motor set. It has the advantage of a large air gap and the power factor of the machine is under the control of the operator. This latter feature, if properly applied, is of great benefit to the transmission line regulation. If induction motors are in use at the same mine, operating the synchronous motor at a leading power factor will greatly offset the lagging wattless component. It requires judgment to secure the best results from this feature. While the corrective effects apparently only benefit the power company, they may be detrimental as well as beneficial, and in order that the power company may secure the greatest benefit, it would be necessary for the attendant to be under the control of the power company, as far as power factor adjustment is

concerned. Standard machines are usually built for operating at unity power factor at full load, and under average load conditions it is possible to operate them at slightly leading power factor without detrimental results.

It is now recognized that a low power factor load is detrimental to the power company, so that such loads are sometimes penalized, the power rate being based on the power factor. Under such conditions it is advisable for the mine operator to utilize the corrective effect of a synchronous machine, so as to offset the lagging effect of any induction motors. It is not always economical to attempt to raise the power factor too high, as the corrective effect obtained from a given wattless component is much less in the regions of unity power factor than elsewhere. Generally speaking a power factor of 90 per cent would be considered good. The efficiency of a synchronous motor will be materially affected

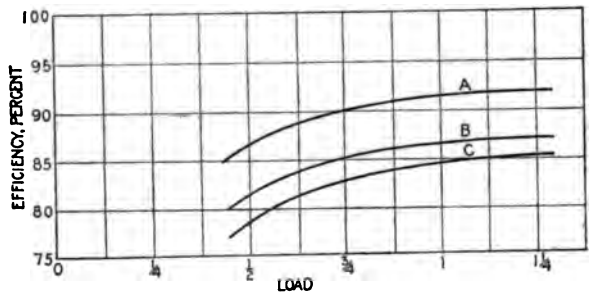

FIG. 1

by over-excitation. Reference to Fig. 1 will show the efficiency curve of a standard synchronous motor-generator set, as built by one manufacturer, when operating at unity and 80 per cent leading power factor.

Synchronous converters are nearly always started from the alternating-current end, and are no more difficult to start than in the preceding cases, except that it is necessary to close the field break-up switch, so that the direct-current polarity will be correct. They have the advantage of large air gaps, and each unit consists of one machine instead of two. The machine itself is much lighter, and requires less energy to bring it up to speed. The 60-cycle converter of today is quite a different piece of apparatus from that of only a few years ago.

Referring again to Fig. 1, curve *A* is the efficiency curve of a standard synchronous converter of the same rating as the motor-

generator set, with transformer losses included. A converter does not lend itself to power factor correction to the same extent as the synchronous motor. The disadvantage of using transformers will be offset by giving the machine a large decree of protection from grounds which might be caused by surges on the high-tension line. It is much easier to run, temporarily, on two transformers than to repair a high-voltage coil in either an induction or a synchronous motor.

A synchronous converter necessarily requires transformers, while both the induction and synchronous motors can be wound for moderately high voltages. Standard mine sets of less than 300 kw. are not wound for voltages in excess of 2200. Therefore, if the voltage is above 2200 transformers will be required in either case, or the machine can sometimes be wound for a higher voltage at an increased cost and reduced efficiency.

In contrast to a motor-generator set, the alternating-current and direct-current sides of a synchronous converter are connected together. The direct-current voltage bears an approximately constant ratio to the impressed alternating-current voltage. In a direct current generator, an increase in voltage with an increase in load is obtained by placing series coils on the field poles, which coils carry all or a portion of the load current. In the converter the same method is used, but the accompanying results are obtained quite differently. Standard synchronous converters are built so as to give flat compounding, maintaining approximately constant terminal voltage. As the direct-current voltage bears a definite ratio to the alternating-current voltage, it is necessary to maintain constant voltage at the collector rings. This is accomplished by having a suitable reactance and a certain minimum resistance in the alternating-current circuit. This reactance may be introduced separately or be in the transformer, line and generator. To maintain constant voltage, the line drop, due to resistance, must not be in excess of 10 per cent. Maintaining constant voltage with varying load by changing the series field excitation will change the power factor. The effect on the line, therefore, is quite different from that caused by a synchronous motor without compounding, as usually built. This results in the difference in corrective effect of the two types of machines. Over-compounded synchronous converters are not standard, because certain limitations peculiar to the type of machine make it undesirable.

In a synchronous converter, part of the alternating current

passes directly to the direct-current end, without circulating through the entire converter windings. The heating capacity of a direct-current generator will depend upon the average heating, while in a synchronous converter it depends upon the heating of the so-called tap coils. Low power factor at full load will cause heavy currents to circulate in the converter winding. As the tap coils must carry this heavy current in addition to the current passing through them, the heating will be above the average of the rest of the winding.

The average mine load, referring particularly to the direct-current load, is usually of a very fluctuating character. Assuming that the field of a synchronous motor is adjusted for unity power factor, say at $\frac{3}{4}$ load with constant excitation, the power factor will be leading at lighter loads and lagging at the heavier loads. A synchronous converter, as generally constructed with varying excitation caused by compounding, will act quite differently, provided, of course, that the line conditions are suitable. As the load falls below the $\frac{3}{4}$ value, the power factor will be lagging, and at full loads, and overloads, slightly leading. Where power is received at high voltages from large transmission lines, the capacity effect may make it more desirable to have a lagging component at light loads and leading at maximum loads. Under these conditions the synchronous converter will give the most desirable performance. However, where large corrective effects are required there is no doubt but that the synchronous motor is the type to be employed. When the synchronous motor receives its excitation from an over-compounded generator the exciting current will increase with the load, thus tending to hold the power factor up on overloads. The synchronous motor-generator set can be successfully operated on a line whose characteristics are such that the operation of a synchronous converter would be unsuccessful. Parallel operation between machines of the same type is practically on the same basis for each of the three types. Parallel operation between machines of the different types is not advisable, as considerable adjustment will be necessary to obtain equal division of the loads.

Cost. A comparison in prices between the induction, or synchronous, motor-generator set, and the synchronous converter, including transformers for the latter, will show that the costs are approximately the same when transformers are not required by the motor-generator set. It is the usual practise for the central station to supply power at 2200 volts, so that it is seldom neces-

sary for the coal company to purchase transformers. In smaller sizes the synchronous converter with its transformers will cost a little more than the motor-generator set, while with the larger sizes, the reverse is true. For the sizes most common for mine work, the motor-generator set will cost less than the synchronous converter with transformers.

The foregoing comparisons show that where the line characteristics are suitable, the operating efficiency and automatic alternating-current line regulation are in favor of the synchronous converter. Where large corrective effects are required on the alternating-current line, compounding is desired on the direct-current machines, and the transmission line characteristics are not of the best, the synchronous motor will prove the most reliable. When the voltage and frequency variations are such as to preclude the successful operation of synchronous apparatus, the induction motor-generator set should be used.

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MINE SUBSTATIONS
Their Construction and Operation

BY H. BOOKER

ABSTRACT OF PAPER

The use of electricity in mines has been making rapid progress throughout the United States. Steam and compressed air are being superseded largely by central station power. Power from a central station requires a substation to supply direct current to operate locomotives, cutting machines, etc. A substation is used to transform high-voltage a-c. power to direct current at 250 or 500 volts.

Substations, when possible, should be located on the surface, because if located underground there is danger from fire, and dampness weakens insulation and causes corrosion of metallic parts. Construction of an underground substation is more costly than on the surface, as there is danger of the roof giving way. The roof should be arched, or built of heavy concrete and the whole station made fireproof.

When substations are located underground it is necessary to carry a high-tension cable through bore-holes. When located on the surface a low-tension cable can be used.

Many accidents occur because of incompetent men. Good salaries should be paid and competent men obtained. Danger warnings should be posted and men taught to consider wires as being "live", thereby lessening accidents.

DURING the last few years the use of electricity in mines has attracted a great deal of attention throughout the United States. This is largely due to the large increase in coal consumption making it necessary to discard the early primitive methods of running and to install modern power equipment, without which it would be impossible to produce the required output with the present supply of labor.

Steam and compressed air have been and are still used to a large extent for the power supply at the coal mines, but there is a growing use of electricity especially during the last two or three years, due to the introduction of central station power which, strange to say, can be sold to a coal mine cheaper than the mine can produce it itself.

The greatest care should be exercised in the introduction of electric power in a coal mine and the very best advice should

be obtained before attempting any electrical installation about a mine. Electric power improperly installed and not properly operated and maintained will no doubt prove a hazard and it is just such conditions that is causing apprehension in some localities regarding the use of electric power in mines.

The danger and unsatisfactory service associated with electric power in the past, has been largely due to the short sighted policy of the coal mining companies in purchasing cheap equipment unsuited to the service and in employing incompetent labor.

A coal mine is the last place where inferior or poorly designed electrical apparatus should be used, as the risk of trouble is too great.

Even with the best designed and best adapted equipment the question of operation and maintenance is one that is often sadly neglected. The matter of compensation is often allowed to play too prominent a part, and the wages offered are such that it is impossible to obtain competent men who will take proper care of the equipment and who will realize the importance of properly maintaining the apparatus.

Rigid, systematic, and careful tests should be made periodically on all moving parts of electrical equipment to insure proper operation and records kept of these tests for future reference.

Warnings regarding the danger of touching wires cables or electrical apparatus should be from time to time pointed out to all workmen in the mine, and in some way kept constantly before them. The primary cause of the majority of accidents, it is fair to say, is partial or complete ignorance. Those unskilled in electrical work should treat all electrical apparatus as alive, as only in so doing lies complete security for them.

The writer proposes to deal with the installation, operation and maintenance of substations around coal mines from the standpoint of the practical operator. Until quite recently the electric power in use at coal mines was produced by small isolated plants located at each mine. With the large increase in production and the combination of many small mines, the central plant idea and the purchase of central station power is rapidly gaining ground.

The use of power from a central plant, or of purchased power, requires a substation to supply direct current to operate the mine locomotives, cutting machines, underground pumps and lights.

A mine substation, in general, consists of one or more motor-generator sets or synchronous converters used to transform high voltage a-c. power to direct current at 250 or 500 volts.

The small isolated plant was generally placed near the pit mouth, provided the coal and water supply was convenient. As the capacity of the mine increased and the distance to the working face became greater the power conditions became quite unsatisfactory. An increase in the capacity of the existing plant often means a large expenditure of time and money so that the purchase of central station power and the installation of a substation offers the best solution. The substation can generally be placed at a more advantageous point than the isolated plant since a substation is independent of coal and water supply. An increase in power supply at any time can be easily and quickly taken care of at a low cost.

Substations when properly designed and installed require little attention, and the attendant is needed only to reset circuit breakers and to see that everything is running properly. If power is not wanted the machines can be cut out and all expense for current stopped. Starting up is a simple matter of closing a switch and full power is available immediately.

With purchased power, the substation system of power distribution is most advantageous for coal companies operating singly or widely separated mines. The operator transfers his responsibility to those whose business it is to carry it, leaving him free to his business of mining coal, thus relieving him of the worry and care of his power plant, and thereby greatly increasing the efficiency of his coal mining department. The operator substitutes his power house with its engineers and firemen and its need for good and abundant water, with a small substation that requires only one attendant and no water supply.

The exact location of the substation is often a hard question to decide. Conditions frequently arise where it would be desirable to install the substation underground, but in general, unless absolutely necessary, the substation should be placed above ground. The preferable location is at the pit mouth when possible, as it can then be looked after by a workman who has other duties to perform. In a small mine the tipple foreman can attend to the station, while in a shaft mine the station should be located in the hoist room and looked after by the hoist engineer. In a large mine requiring more than

one station, they should be located centrally to the work to save the expense of heavy copper feeders. The substation can often be located near the fan so that the same operator can look after both. When the d-c. feed wires cannot be carried into the mine by one of the openings, bore holes can be used, as it is comparatively simple to maintain a 500-volt cable installed in a bore hole.

In regard to locating the substation underground there are many objections to this. Beside the source of danger from fire there is most always considerable dampness underground which not only weakens the insulation but causes corrosion of unprotected metallic parts. It is practically impossible to make an underground substation free from moisture, and good ventilation is often difficult to obtain. This matter of ventilation is very important as the heat losses in the apparatus must be carried away so that the capacity of the machines will not be impaired. This question will be readily appreciated when it is considered that one kilowatt loss per minute is equal to 57 B.t.u., which is equivalent to heating about 3001 cu. ft. (84 cu. m.) of air one degree fahr. per minute. The total loss in a 200-kw. station will be approximately 15 kw. The heat generated will, however, help to keep the substation dry in conjunction with proper drainage and pumping.

All underground substations should be ventilated with intake air and all high-tension cables should, when possible, be carried to the substation in the intake airway. This may work a hardship particularly if the mine is shaft operated and a blowing fan is used, as it is practically impossible to maintain wires in a shaft of this kind on account of the high air velocity. The writer knows of mines of this type where it is unsafe for a man to attempt to ascend the stairway, much less do any work while the fan is in operation.

Very often considerable coal dust and pure sand is picked up by the air currents which is a rather severe matter, as the dust and sand plays havoc with the bearings and oiling systems.

A very important point regarding the construction of an underground substation is the cost of construction, which is considerably greater than building on the surface. Since there is always danger of the roof giving way, the roof should be arched or built of heavy reinforced concrete and the whole station made fire proof. For a 200-kw. substation the dimensions should not be less than 24 by 24 by 12 ft. (7.3 by 7.3 by 3.6 m.) high.

With the substation located underground it is generally necessary to carry a high-tension cable through a bore hole. With the station located on the surface this cable will be a low-tension cable and there will be no trouble to maintain it. A satisfactory method is to use "lead" covered cable attached to a messenger cable about every 30 feet by wiped joint or suitable clamps which will not injure the lead. The high-tension cable is much more difficult to maintain, and most mine electricians know what it means to maintain high-tension insulated cable in deep shafts and in bore holes.

The question of attendance for an underground substation is a serious one and actual experience has taught the writer that it is impossible to get men underground to give machinery the same attention they will give it on the surface. This is particularly true of the night shift, as it has been found that there is a greater tendency among men to sleep on the night shift in mines, than on the same shift outside. This may be due to the mine atmosphere, which is often contaminated with gas from gob workings.

In regard to the general design and construction of a mine substation, space economy should be given consideration, but care must be exercised to see that there is plenty of room for making repairs and replacements.

The operating requirements of a substation in regard to continuous service may vary from a few hours per day to practically continuous service. As due provision must be made for inspection and repairs it is quite evident that in case of continuous operation, attention must be given to the proper sectionalization of the apparatus and duplication of the equipment.

A very important point to consider is the relative attention that will be given to the operation of its station by the consumer and the central station company. It is only natural that the consumer will want to supervise the operation of his own station so that it is evident that any complications in switching equipment and control apparatus should be avoided.

The substation should be constructed of fireproof material, and all high-voltage apparatus should be enclosed to secure maximum safety to attendants. Asbestos lumber should be used for partitions and doors, which serves as a protection against shock and is a valuable protection in case of fire.

The common faults in electrical installations of this kind are as follows:

Exposure of high and medium pressure conductors at the surface and high and medium pressure switching gear underground.

The frames of high and medium pressure apparatus not properly grounded. All machine frames should be well grounded.

Switches, cables, rheostats, starting boxes, etc., mounted on wood and surrounded by as much wood as possible, the whole often resulting in two occurrences; first, a shock by coming in contact with an exposed live part; second, fire due to defective joints in cables.

Omission of tubes, where frames of machines and brattices are pierced by cables.

The common defects of organization are as follows:

The absence of trained electricians.

The handling of live wires or apparatus for adjustment or repair when not absolutely necessary.

The absence of a definite and distinct rule that unskilled men may handle electrical cables and apparatus only when the power is off.

The use of central station power will no doubt bring the operating force at the mine in close touch with the central station operating force which is always ready and willing to advise the coal operator in regard to his installation and operation.

It is to be hoped that improved legislation and a better cooperation between the mining companies and the Bureau of Mines will greatly increase the safety and improve the operating conditions in connection with the use of electricity in mines.

DISCUSSION ON "MOTOR-GENERATOR SETS VS. SYNCHRONOUS CONVERTERS IN MINE SUBSTATIONS" (HOEN), AND "MINE SUBSTATIONS; THEIR CONSTRUCTION AND OPERATION" (BOOKER), PITTSBURGH, PA., APRIL 10, 1914.

W. A. Thomas: Unquestionably from the standpoint of economy the synchronous converter is superior to the motor-generator set, but in a careful analysis of the mining conditions, and the ultimate results to be accomplished, the question of the kilowatt-hours per ton in transformed energy constitutes a relatively small proportion of the total cost. The method of distribution of the direct current which has been converted has a great bearing on this question. As pointed out in Mr. Hoen's paper, the energy in the small mine is carried through one opening which is the main entry, and when the bituminous mine, particularly, as distinguished from the anthracite mine, comes to the commercial condition requiring electric haulage, the power is mainly consumed some distance from the entry. The distance of the point of consumption from the mine entry in the average bituminous field is probably upwards of a mile.

This gives rise to the necessity of over-compounding in order to maintain a fairly constant voltage at the point of consumption, and even at that it is not practicable to put in a distribution of copper in the mine to maintain much less than 10 per cent variation in voltage at the point of consumption.

It is for this reason that the motor-generator set is undoubtedly more popular in mining work than the synchronous converter, and this is particularly true of the bituminous mines, where large areas are worked out due to the thinness of the coal. There is, however, a field for the synchronous converter where several openings are served from one station, in which case a flat voltage is desirable. The question of efficiency of the converter over the motor-generator set is offset, to some extent, by the introduction of the over-compounding, so that at maximum load the losses due to the 10 per cent higher voltage transmission are less than on the flat compounding with the corresponding load on the station.

A particular point of advantage in the synchronous motor-generator set as brought out by Mr. Hoen is the power factor correction, and in this connection there is an interesting development which I think is followed by practically all manufacturers at the present time, and particularly in the low-voltage motor-generator set, of exciting the synchronous motors from the over-compounded generator, so that the field adjustment of the synchronous motor is made for good power factor at light load, and the 10 per cent over-compounding of the generator compensates for the increased load on the synchronous motor by bringing up its field excitation. That is being given study, and the suggestion has been made that in the use of 500- to 600-volt sets where a separate exciter is necessary similar results

can be obtained by one of two methods, either to put a series winding, auxiliary to the shunt winding, on the field of the exciter, the current in which shall be proportional to the load on the direct-current generator, so that in a similar manner the exciter voltage is brought up with the load on the set; or, another, and perhaps a more advantageous way of doing this is to excite the field of the exciter from the generator so as to get the benefit of the over-compounding by raising the excitation on the shunt field of the exciter. This would prove to be advantageous, doubtless, in railway work, as well as where the loads are greatly fluctuating, and where it would not, perhaps, be advantageous to run the excitation of the synchronous motor at maximum at all loads.

P. M. Lincoln: I have always felt pretty strongly about this matter of synchronous converters as compared with motor-generators where the problem is simply one of transposing alternating current into direct current. I have always felt that the synchronous converter had so many advantages over the motor-generator that there was no question about it. There are certain disadvantages, of course, connected with the synchronous converter when it is used. One of these disadvantages is that it is impossible to give it a high over-compounding, and if over-compounding is essential to the use of direct current in mines, that simply means that the synchronous converter is not available.

While I am rather familiar with the apparatus used, yet I will have to confess I am not at all familiar with the actual conditions that exist in mines, and so I am unable to express an opinion on the necessity of this very high over-compounding, which seems to be the general reason for demanding motor-generators rather than synchronous converters for mining work. The only thing that makes the motor-generator more applicable and better adapted to that duty is, as I said before, the necessity for that high over-compounding. If you can get away from the necessity for high over-compounding, I do not think there is any question, in general, that the synchronous converter will be much better for the purpose of getting the direct-current supply than any other piece of apparatus.

N. Stahl: Much of the emphasis of the superiority of motor-generator sets to synchronous converters for mine operation is laid on the over-compounding feature. As Mr. Lincoln has pointed out, it is undesirable, but not impossible, to over-compound the synchronous converter, even for cases where the rise only amounts to 10 per cent at full load. The difficulty arises from the fact that so large an amount of reactance is required; so that practically it leaves an undesirable feature on account of the excessive currents which flow in the tap coils of the converter at high load when you have a considerable amount of leading power factor current. The advantage, however, of the higher voltage procurable by the over-compounding of the motor-

generator can largely be eliminated by the very simple device of operating your converter at as high a flat-compounding voltage as you will get at the full-load condition on the over-compounded generator. Inquiry develops the fact that both the synchronous converters, now standard for mine work, and the motors standard for mine work, are applicable for this higher voltage condition under light load, so that excessive bucking or flashing or commutation trouble is not to be expected. That being the case, the argument in respect to the average voltage on the direct-current line is in favor of synchronous converters, which permits a comparison more or less on the basis of the curves presented in Mr. Hoen's paper, which show, for a load, on the average, of three-quarters full load, about 7.5 per cent advantage in favor of synchronous converters, plus transformers, over the synchronous motor, running without transformers; but, bear in mind that in many cases transformers will also be required with the motor-generator, which will make the discrepancy still greater in favor of the synchronous converter.

If you evaluate for a particular case of an average synchronous converter substation capacity of 200 kw., on the basis of three hundred working days of ten hours each, and a load factor of 25 per cent—which presumably might be much better, particularly if advantage is taken of the present tendencies in design to construct machines which will carry safely 200 per cent overload for such length of time as is necessary for the accelerating of trains—you will find, on a one cent per kw-hr. basis, there will be a difference in cost of power per year of about $160, which represents about 6⅔ per cent of the presumptive first cost of substation equipment which, by Mr. Hoen's figures, are placed at about a parity, with a tendency, however, towards an initial cost preference in favor of the converter and transformers, over the motor-generator alone, as the capacity increases.

The question of the power factor correction by the two devices has been raised. Mr. Thomas brought up the point that by the automatic over-compounding of the excitation of the synchronous motor directly from the generator or otherwise, through an exciter—which, by the way, increases the cost of the motor-generator set—much of the inherent automatic tendency of the converter toward a movement of the power factor through lagging values, at no-load, toward leading values at high load, may be secured on the motor-generator. To that no exception can be taken, so far as it goes. There is, however, an inherent tendency on the part of the operating man not to over-excite his machine, regardless of his instructions; that is, if his machine is operating on the basis of 80 per cent leading power factor at full load, the tendency is to get it as close to unity as possible, and let it stay there, or else under-excite the machine, on the mistaken notion that over-excitation

would force the field too hard, thus making the system power factor worse instead of better.

While there is no question of the ability of the synchronous motor, properly handled, to effect better conditions at the power house, taking them as they are under present conditions, yet the integrated values for the ordinary set will show, I think, a predominating influence in favor of the synchronous converter.

W. A. Thomas: From a theoretical standpoint, the contention of Mr. Stahl is absolutely correct, but when we take into account the fact that the connected apparatus on a substation ranges from 50 to 180 per cent over the capacity of the substation, and the fact that the average load factor of such a substation is about 35 per cent of its capacity, we have a condition in which with constant voltage, motors which are attached to that line are subjected to an over-voltage. In other words, if we take the voltage which is now practically standard in coal mining service, namely, 275 volts in one class, and 600 volts in the other class, we find the apparatus, the commercial motors, for pump driving, fan driving, and for cutting machines, ranged from 210 to 250 volts. The industrial motor, so-called, for driving pumps and fans, is standard at 230 volts. It is true you can get motors wound to 250 and 275 volts, on their fields, but it means ordering these motors specially, as no standard of this character has been established which is carried in stock.

In the buying of a pump, for instance, the proposition is taken up with a pump manufacturer, and he buys a motor from the local stock of the manufacturer with the result that he gets a standard motor of 230 volts in the low-voltage class, or 500 volts in the medium-voltage class. The result is that when he has a flat voltage of 275 or 500 volts and when the load is light on the station, he will get the full voltage of the circuit on his motor field. This is also true of the night cutting of coal, where the load is relatively small, unless an adjustment is made of the voltage at the power station with a flat-compounding system. That adjustment, in the case of a converter substation, requires either a regulator or a shifting of the voltage taps applied to the synchronous converters. It is for these reasons, mainly, that in the installation of substations the use of the motor-generator predominates.

N. Stahl: There is one point in connection with the converter substations which should be mentioned. The use of synchronous converter substations in mines necessitates the use of two banks of transformers, in the event of the power being fed in at higher voltage than 2200. One bank would be necessary for feeding the local mine circuit and the other bank for feeding the synchronous converters. That adds to the first cost.

Will M. Hoen: From personal experience in metal mines, where the conditions are better than in coal mines, I think an underground substation, particularly in a coal mine, should always be avoided if possible.

In regard to motor-generator sets and synchronous conver-

ters, the intention was merely to show that the electrical work being done in mines nowadays is better than it was a few years ago. Formerly one generator was put in the mine entrance, copper was stretched through the mine, and things gradually grew on to the system. Nowadays, in the better class of mines, with the use of substations, their location and the distributing system can be advantageously planned; so that the question of using excessively over-compounded voltages should become of less interest. It undoubtedly is true that the majority of the substations have motor-generator sets, and use over-compounded voltages. This requirement is generally necessary on account of locomotives which require direct-current. Although a large amount of copper may be installed, the track circuit is in bad condition, and this generally accounts for the large voltage variations.

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MAGNETIC AND OTHER PROPERTIES OF ELECTROLYTIC IRON MELTED IN VACUO

BY TRYGVE D. YENSEN

ABSTRACT OF PAPER

Electrolytic iron of a purity of 99.97 to 99.98 per cent was melted in fused magnesia crucibles in a modified Arsem furnace, forged into rods, machined, and annealed in an electric furnace according to various heat cycles.

The magnetic properties were obtained by the Burrows double bar method. Determinations were also made of the electrical resistance, chemical composition, and physical properties, including microstructure and critical temperatures as well as tensile tests. A few commercial iron and steel samples were tested for comparison.

The following valuable results were obtained:

1. Pure iron melted in an atmosphere of carbon monoxide under atmospheric pressure will absorb both carbon and oxygen with the result that the iron thus produced is of an inferior magnetic quality.
2. Low-carbon iron melted in vacuo will lose 50 to 90 per cent of its original carbon content.
3. The magnetic quality of electrolytic iron melted in vacuo is decidedly superior to any grade of iron thus far produced, the maximum permeability obtained being 19,000 at a flux density of 9500 gausses. The average hysteresis loss obtained is less than 50 per cent of that found in the best grade of commercial transformer steel, due to the fact that the coercive force is very much lower than for silicon steel, although the retentivity is higher.
4. The specific electrical resistance of pure iron melted in vacuo is 9.96 microhms per centimeter cube.
5. Swedish charcoal iron melted in vacuo has a magnetic quality approximating that of electrolytic iron melted in vacuo, chiefly due to the reduction of the carbon content.

The author suggests that the high electrical conductivity and hence large eddy current losses in this material may possibly be greatly reduced by the addition of silicon or aluminum without very materially affecting the magnetic quality.

PREVIOUS to the beginning of the twentieth century Swedish charcoal iron was the best grade of iron that could be found for magnetic purposes. About that time Hadfield[1] produced a number of iron alloys that revolutionized the iron industry so far as magnetic iron was concerned. His 2.5 per cent silicon alloy and 2.25 per c nt. aluminum alloy showed

a higher permeability and gave a lower hysteresis loss than the purest Swedish iron. Perhaps even more important was the high electrical resistance of these alloys, reducing the eddy current loss to one-third or less of that of the Swedish iron under identical conditions. At the same time Barrett[2] showed that the increase in electrical resistance due to the addition to pure iron of one per cent of any alloying element is inversely proportional to the atomic weight of that element.

Since the time of the appearance of Hadfield's alloys comparatively little improvement has been made in the magnetic quality of the iron and iron alloys. What has been done has mostly been in the way of modifications of Hadfield's silicon steel. In 1906, however, Professor C. F. Burgess[3] of Wisconsin commenced a series of investigations upon the magnetic and allied properties of electrolytic iron and its alloys with other elements. While the improvement made by Burgess were not revolutionizing, his investigations, I think, have pointed out the direction in which improvements may be expected. In 1910, E. M. Terry[4], also of Wisconsin, investigating the effect of temperature upon the magnetic properties of electrolytic iron as deposited, found that this iron, after annealing at 1100 deg. cent. and slow cooling, has a very high permeability and a low coercive force. On account of its high retentivity, however, the hysteresis loss was found to be higher than for Swedish charcoal iron.

In 1911 the writer commenced an investigation of the magnetic properties of iron in the Electrical Engineering Department of the University of Illinois. Doubly refined electrolytic iron, deposited according to the methods used by Burgess, has formed the basis for the investigation. It was deposited from Swedish charcoal iron, of the following composition:

C	0.163	per cent
Si	0.032	" "
S	0.0002	" "
P	none	
Mn	none	
Fe (by difference)	99.8	" "

1. Barrett, Brown and Hadfield, *Jour.* Inst. Elec. Engrs., Vol. 31, p. 674, 1902.

2. *Proc.* Royal Society, Vol. 69, p. 480, 1902.

3. See *Electrochem. & Metal Ind.* for 1909 and 1910. A series of articles by Burgess and Aston.

4. *Phys. Rev.*, Vol. 30, p. 133, 1910.

The doubly refined iron contains:

C	0.006	per cent
Si	0.01	" "
S	trace	
Fe (by difference)	99.98	" "

The crucibles used were made from electrically fused magnesia containing about two per cent silica, and these crucibles were placed in graphite crucibles and securely covered. At first a

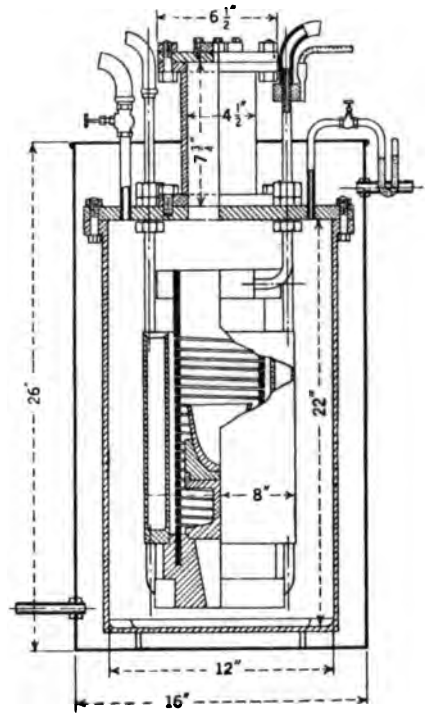


FIG. 1—VACUUM FURNACE

Hoskins resistance furnace was used for the melting of the iron but this was abandoned after a large number of attempts had been made to keep the iron from being contaminated. If the crucibles were left exposed in the furnace the iron was so badly oxidized that it cracked to pieces under the hammer in the attempt to forge it. If buried in crushed carbon the iron absorbed comparatively large quantities of carbon. Burgess used the latter method and found that the iron absorbed from 0.05 to 0.15 per cent carbon, probably by reducing the carbon monoxide

gases surrounding it. The results obtained by the writer agree with those obtained by Burgess, so far as the carbon is concerned, but as will be shown later, carbon alone does not account for the properties of the iron thus produced.

In order to overcome the difficulties above referred to, a vacuum furnace was constructed in the shops of the department. It is modeled after the Arsem type of furnace, and is shown in Fig. 1 and Fig. 2. The inside parts consist entirely of graphite cut from solid graphite electrodes, with the exception of the water-cooled copper tubes, that serve as supports as well as leads. A Geryck pump is capable of maintaining a pressure of 0.5 cm. or less with 500 to 600 grams of molten iron in the furnace. The

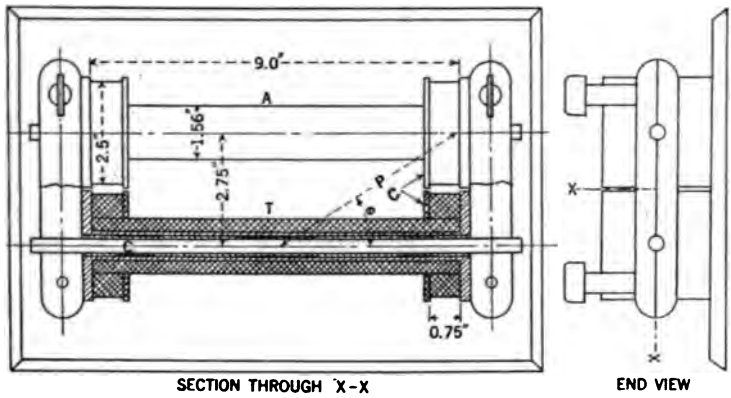


FIG. 3—PERMEAMETER

state of the charge may be observed through a mica window in the top.

While the results obtained with this furnace are not as uniform as might be desired, it must be remembered that the tests have necessarily been made upon relatively small samples, that the processes involved in order to obtain the test pieces in the final condition are numerous, and that the magnetic properties of this material are very readily affected by outside influences. The chemical composition of the final iron is quite uniform.

METHOD OF MAGNETIC TESTING

A number of different instruments for the magnetic measurements were tried and discarded. The main defect of most of them was that large and uncertain corrections had to be made to

the readings in order to arrive at the correct results. As it was desirable to make a large number of test pieces, Rowland's ring method was impracticable on account of the difficulty of construction, and also because of the difficulty of electrical resistance measurements. An instrument was needed that could measure accurately the magnetic properties of relatively short rods. The one finally decided upon was constructed by the writer in the shops of the department in accordance with the recommendations of the Bureau of Standards.[5] The details of this instrument[6] are shown in Fig. 3 and a diagram of the con-

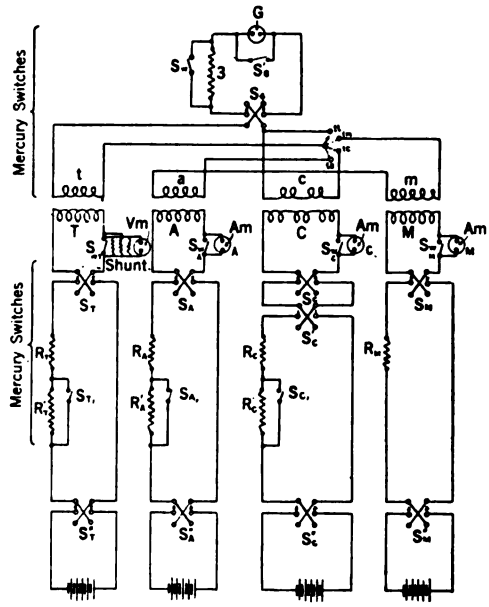


FIG. 4—ELECTRICAL CONNECTIONS FOR PERMEAMETER

nections in Fig. 4. Briefly stated, it consists of a double bar and yoke with one main solenoid T, and one auxiliary solenoid A, separately controlled, and four compensating solenoids, C, next to the yokes connected in series. Each of these coils was wound with No. 18 B. & S. gage double-cotton-covered wire in 10 layers of exactly 20 turns per inch (= 7.875 turns per cm.). By means of the three secondary coils, t, a and c, the magnetic flux

5. *Bulletin*, Bureau of Standards, Vol. 6, No. 1. Reprint No. 117.

6. For further information regarding the various apparatus and instruments here described, the reader is referred to Bulletin No. 73 of the Engineering Experiment Station of the University of Illinois.

can be investigated at different points of the magnetic circuit and equalized by adjusting the currents in the magnetizing coils. With no leakage of flux, the magnetizing force for the rod measured is

$$H_T = 0.4\pi\, n_T\, I_T$$

where n_T = number of turns per cm. of main solenoid,
I_T = current in main solenoid in amperes.

This is strictly true if the effects of the ends of the various magnetizing coils are negligible. These end effects have been calculated and the correction to be applied to H_T found to be less than +1 per cent for ordinary iron for all values of H. For the highest permeability iron found in this investigation, however, the correction for low values of H, on account of the high compensating currents required in coils C, has been found to vary from +4 per cent for low values of H to less than +1 per cent for values of $H = 8$ or above. For reasons to be given presently, these corrections have not been made in the results given in this paper.

For the determination of B a ballistic galvanometer of a 15-second period was at first employed. This was calibrated by means of a mutual inductance, consisting of a primary coil, M, 10 cm. in diameter and 90 cm. long, of No. 18 B. & S. double-cotton-covered wire, 20 turns per inch (=7.875 turns per cm.), with a secondary m, of 1260 turns of No. 30 double-silk-covered wire, wound in 10 layers occupying 8 cm. at the center of the primary. The error due to the end effects of this coil is such that if it be assumed that the magnetizing force H_M at the center of the calibration coil M is

$$H_M = 0.4\pi\, n_M\, I_M$$

then the values found for B_l of the rod tested are high by 0.3 per cent.

The ballistic galvanometer served the purpose very well until the electrolytic vacuum iron was ready to be measured in the annealed state. On account of the high permeability and low electrical resistance of this iron, the change of magnetism was found to be too sluggish for accurate determinations with a ballistic galvanometer. This was particularly true for hysteresis determinations. Five or six seconds were sometimes required for the flux to complete the change, so that by

the time the galvanometer coil had reached its maximum deflection the flux was still changing. It was, therefore, very evident that the galvanometer had reached its limit of usefulness, even though its period had been doubled.

To overcome this difficulty a Grassot fluxmeter was used for all the final measurements. In this instrument the suspension effect has been practically eliminated, and its deflections are independent of the time required by the flux to complete the change.

All the different connections for operating the permeameter are made through rocking mercury switches operated by means of keys similar to piano keys. In this manner any number of switches may be operated simultaneously, and comparatively little time is occupied in making the adjustments. A view of the operating table is given in Fig. 6.

The magnetization curves are obtained by the method of reversal, by first adjusting the currents in A and C until the flux is equalized at all parts of the magnetic path.

The hysteresis loops are determined in a similar manner, but instead of going from $+H_{max}$ to $-H_{max}$, the change is made by inserting the resistances R'_T, R'_A, and R'_C in the magnetizing circuits by opening the switches S_{T_1}, S_{A_1} and S_{C_1} either alone or simultaneously, with the reversing switches S_T, S_A, and S_C. In this manner the change is always made from H_{max} to the various points on the loop, and the effect of the viscosity of the iron is eliminated.

In Fig. 5 are shown three magnetization curves for the standard rod, No. 3-33 B. One is drawn according to the certificate supplied by the Bureau of Standards for this rod. The other two were obtained by the writer, in one case by using the Grassot fluxmeter and in the other by means of the ballistic galvanometer. There is some doubt as to the case of the discrepancy for low and medium densities between the curve as obtained by the Bureau and that obtained by means of the fluxmeter. On this account the corrections above referred to have not been made, as the writer feels that, if his results be slightly in error, the error is on the safe side.

Details of the Experiments

The electrolytic iron previous to being placed in the crucible to be melted was crushed into small pieces and thoroughly cleaned with hydrochloric acid, boiling distilled water, and

alcohol. It was then transferred to the crucible, covered with a magnesia cover and placed in the vacuum furnace. The furnace was exhausted immediately and heated up, slowly at first, so as to give the absorbed gases time to escape without too much loss of vacuum. With the furnace at a dull red heat the melting would then require about ½ hour with an input of 15 kw. In order to insure homogeneity 12 kw. was left on for another 15 minutes and the furnace then allowed to cool.

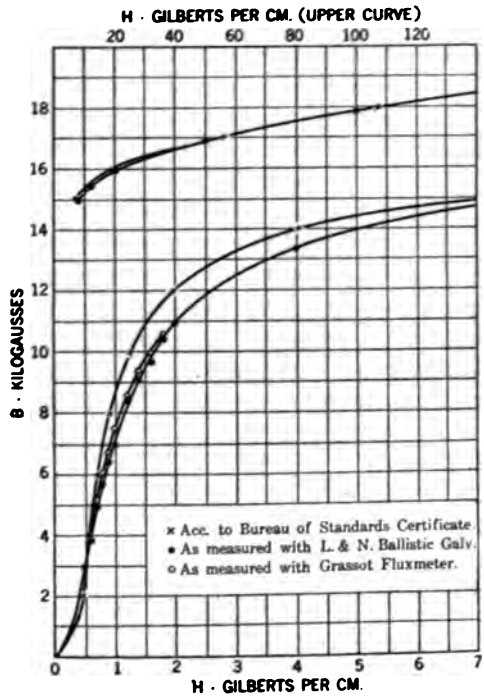


FIG. 5—MAGNETIZATION CURVES FOR STANDARD ROD NO. 3-33B

When removed from the furnace the ingots were as bright as silver and so soft that they could be cut with a knife. They were reheated in a coke forge to ordinary forging temperatures, 1000 to 1100 deg. cent., and forged into rods about ½ in. by 20 in. (1.25 by 50 cm.).

From these rods the following test pieces were prepared:

1. The magnetic test piece, serving also for the electric tests, 0.392 in. (0.996 cm.) in diameter and 14 in. (35.5 cm.) long.

2. Two test pieces for the mechanical tests. These had a

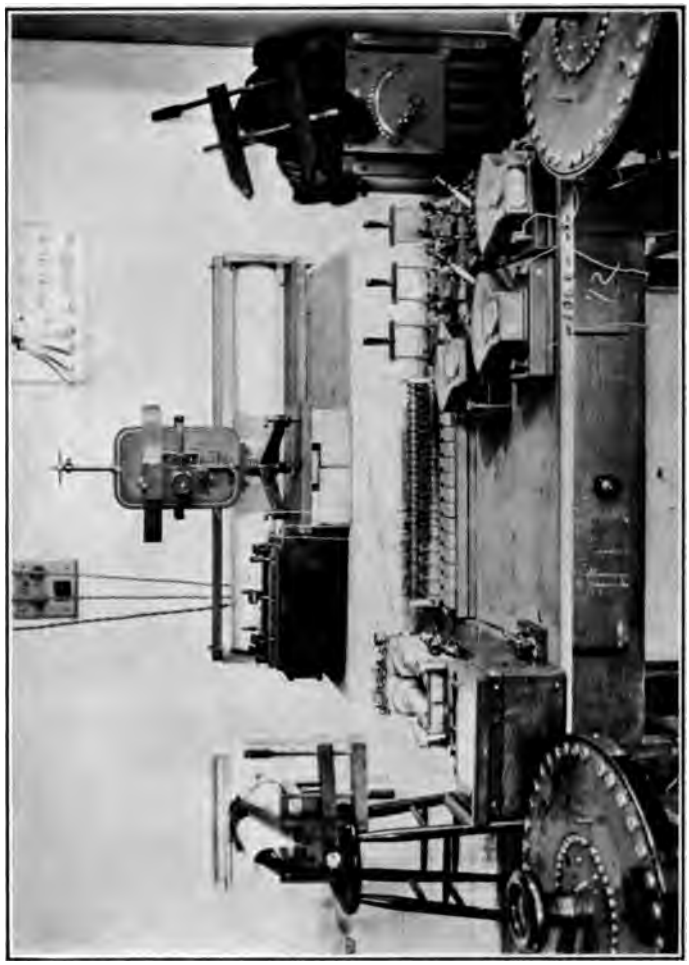


FIG. 6—OPERATING TABLE FOR MEASUREMENTS WITH PERMEAMETER [VENSEN]

FIG. 2—VACUUM FURNACE, INSIDE VIEW [VENSEN]

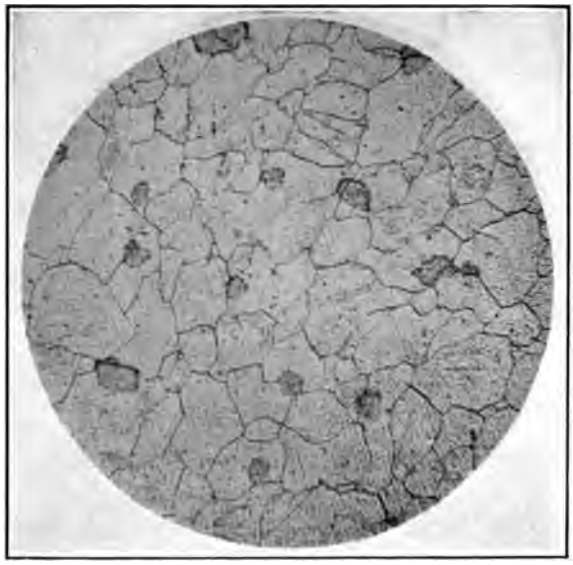


FIG. 13—ROD NO. 3-39A. AS FORGED; ELECTROLYTIC IRON MELTED IN VACUO. MAGNIFIED 60 DIAMETERS

[YENSEN]

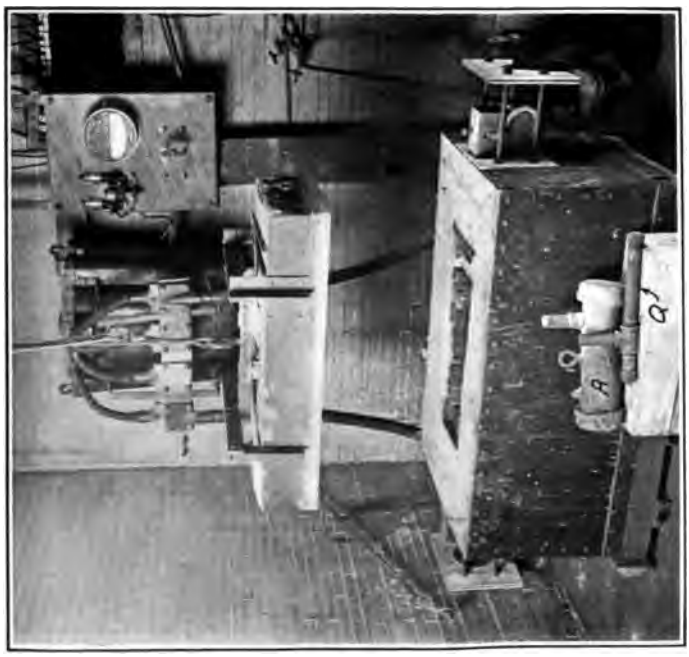


FIG. 7—ANNEALING FURNACE

[YENSEN]

middle section 0.3 in. (0.76 cm.) by 1½ in. (3.8 cm.), with threaded ends, ½ in. by ½ in. (1.25 cm.).

3. One test piece for the study of the microstructure, ½ in. by ½ in. (1.25 cm.).

4. One test piece for the critical temperature determination.

For the chemical analysis the shavings obtained from the preparation of these test pieces were collected, after first removing the outside coating of oxide.

After being tested as forged, the test pieces (1 and 3 above) were sent through different heat treatments. If they were to be annealed they were packed in pulverized magnesia in an iron cylinder, *A*, and placed in the annealing furnace shown in Fig. 7. In order to minimize the formation of oxide the magnesia was moistened with alcohol to drive out the air. After reaching the annealing temperature desired, the cooling was done, in all but the preliminary tests, in accordance with definite cooling curves. The temperature was measured by means of a platinum-platinum +10 per cent rhodium pyrometer, calibrated from time to time.

Quenching was done by placing the test pieces in the cylinder *Q*, Fig. 7, filled with magnesia and moistened with alcohol. When the desired temperature was reached, the cylinder was removed from the furnace, tipped up, and the contents plunged into the quenching bath by means of a sharp blow on the top of the cylinder.

As mentioned above, a small specimen was prepared for the critical temperature determinations of each rod. These determinations were made by placing the specimen in a ½-in. (1.25-cm.) "electroquartz" pyrometer tube, with the hot junction of the pyrometer inserted in the small hole made in one end of the specimen. The tube was partly filled with fused magnesia and placed in a Hoskins muffle furnace with the end at the middle of the furnace. The temperature was gradually raised to about 1000 deg. cent., the current cut off and the furnace allowed to cool naturally, while the time interval for each 10 deg. cent. was obtained by means of two stopwatches. From the data thus obtained three different curves were plotted for each specimen, namely, (1) the temperature-time curve, using temperature as abscissa and time as ordinate; (2) the temperature-rate curve, using temperature as abscissa and the number of deg. cent. fall in temperature per minute as ordinate; (3) the temperature inverse rate curve, using temperature as

abscissa and number of seconds per deg. cent. fall in temperature as ordinate. From these curves the critical temperatures can readily be located.

While this method is not as accurate as the differential method by means of three thermocouples, it serves as a check upon the other determinations made in the course of the investigation.

From the chemical analysis of the Swedish charcoal iron and the doubly refined electrolytic iron it is seen that the only mea-

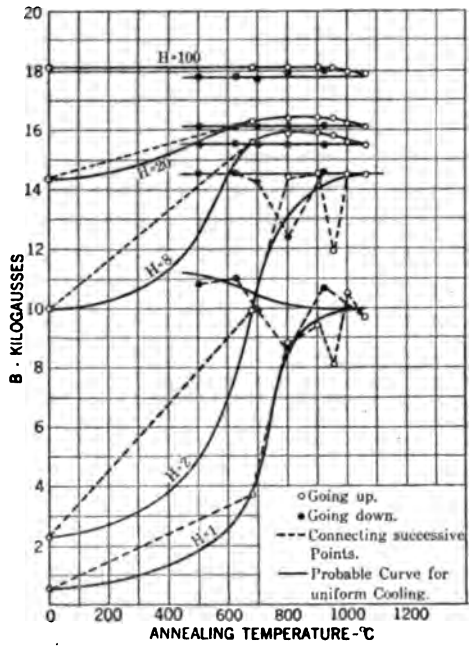


FIG. 8—EFFECT OF ANNEALING TEMPERATURE UPON PERMEABILITY, ROD NO. 3-39

surable impurities in the latter are carbon and silicon. As these are the only impurities that are liable to be affected during the processes described, it seemed superfluous to analyze for anything except carbon and silicon. A few analyses were made for sulphur, but only traces could be found.

All the rods tested have been analyzed for carbon by direct combustion. On account of the small quantities dealt with, extreme care had to be used in these analyses.

Results

The results of the investigation are embodied in the following tables and figures. In order to ascertain the most favorable

TABLE I.
SUMMARY OF RESULTS
Rods Thoroughly Annealed at 900 Deg. Cent.

Rod No.	Description of iron	Furnace used for melting	Carbon as per chemical analysis, per cent	Max. permeability	Flux density for max. perm.	Hysteresis loss, ergs per cu. cm. per cycle		Coercive force for Bm = 15000	Retentivity for Bm = 15000	Spec. elect. resist. at 20° C. microhms	Crit. temp Ar_3 deg. cent.
						Bm = 10000	Bm = 15000				
3-38	Electrolytic	Vacuum	0.0104	19000	9500	813	1640	0.295	12100	10.0	905
3-39	"	"	0.0110	16500	8500	880	1860	0.32	12600	9.95	905
3-34	"	"	0.0090	16000	6500	895	1600	0.30	10600	10.2	895
3-49	"	"	0.0120	15400	5000	902	1710	0.31	8100	9.9	
3-31	"	"	0.0120	13100	6200	980	1760	0.32	9100	10.03	885
3-43	"	"	0.0196	12900	5500	1165	2180	0.40	10200	9.85	895
3-48	"	"	0.0080	12600	5500	955	1850	0.29	9300	9.7	
3-36	"	"	0.0150	12250	6000	953	1830	0.33	9000	10.16	875
3-40	"	"	0.0110	12000	9000	1240	2500	0.36	10100	9.7	895
3-47	"	"	0.0080	11900	8000	1190	2120	0.35	9000	10.05	900
3-50	"	"	0 0099	11600	5000	995	1940	0.30	9000	9.7	
3-41	"	"	0.0095	11250	4500	1155	2180	0.40	10000	10.0	895
3-30	"	"	0.0090	11050	5500					9.94	
3-45	"	"	0.0080	10500	9000	1470	2640	0.40	10600	9.87	895
3-37	"	"	0.0450	8050	4500	1255	2000	0.40	9500	10.3	885
Avg.	"	"	0.0125	12950	6550	1060	1990	0.34	9940	9.96	894
Avg. for Iron melted in resist. furnace			0.1000	1965	3930					13.53	
3C01	0.05%C added	Vacuum	0.0130	8600	6000	1405	2300	0.40	10000	10.24	895
3C02	0.10%C added	Vacuum	0.0120	7600	7000	1710	3190	0.50	10700	10.64	895
3C03	0.50%C added	Vacuum	0.1810	4400	5500	1910				12.40	
1-21	Sw. charc. iron remelted in vacuum		0.0080	10350	7000	1290	2640	0.48	11200	10.30	
Comm	ercial Grades										
SwI-4	Sw. charc. iron cut from plate.		0.1630	4870	6600	2490	4530	0.95	8000	10.57	
G1&2	Stand. transformer steel*			3850	7000	3320	5910	1.33	9900	11.09	
H1&2	4 per cent silicon steel.*			3400	4300	2260	3030	0.88	5400	51.15	

*Received manufacturer's standard anneal.

annealing temperature, one of the rods, No. 3-39, was annealed at a number of different temperatures ranging from 500 deg. to 1060 deg. cent., in every case followed by a natural cooling of the furnace. The result is shown graphically in Fig. 8.

Based upon the results obtained with No. 3-39, the 15 rods made from electrolytic vacuum iron were tested after various heat treatments. The final heat treatment received by all of the rods consisted in annealing at about 900 deg. cent. and cooling in 48 hours according to a straight time-temperature curve, connecting 900 deg. and 200 deg. cent. To give the details of the results obtained after the various treatments, would be beyond the scope of this paper, and only the final results can be included. In Table I the rods have been arranged according

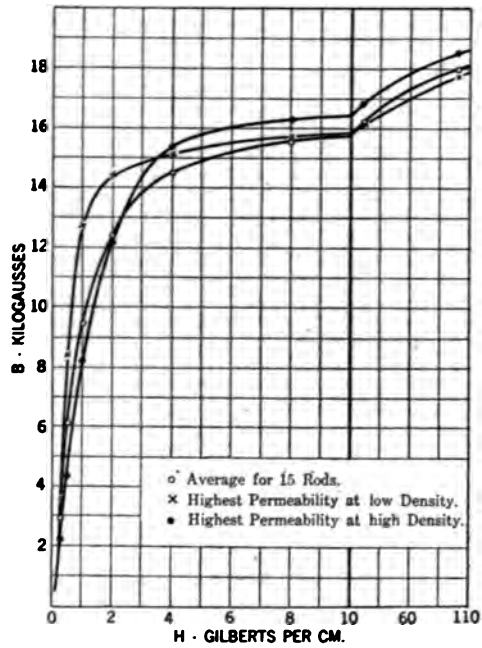


FIG. 9—AVERAGE AND HIGHEST MAGNETIZATION CURVES FOR ELECTROLYTIC IRON MELTED IN VACUO

to the maximum permeability obtained for each rod, and this shows the hysteresis loss and other magnetic data, as well as the carbon content of the rods and their electrical resistance. The last column gives the critical temperature Ar_3 whenever measured. Fig. 9 shows the magnetization curves for the average and best electrolytic vacuum iron, and Fig. 10 shows the hysteresis loops and permeability curve for the best rod, No. 3-38.

For the sake of comparison a number of other rods have been

tested and the results included in this paper. Sw.I-4 is a rod cut from a plate of Swedish charcoal iron, and No. 1-21 is made from iron cut from the same plate as Sw.I-4 and directly next to it, but remelted in vacuo. No. 3C01, No. 3C02 and No. 3C03 are three rods made from electrolytic iron with additions of 0.05, 0.10 and 0.50 per cent carbon, respectively, and melted in vacuo. G-1 and G-2 are two rods made from such commercial bars as are generally rolled into sheets known as "standard electrical sheets." H-1 and H-2 are rods made from bars containing

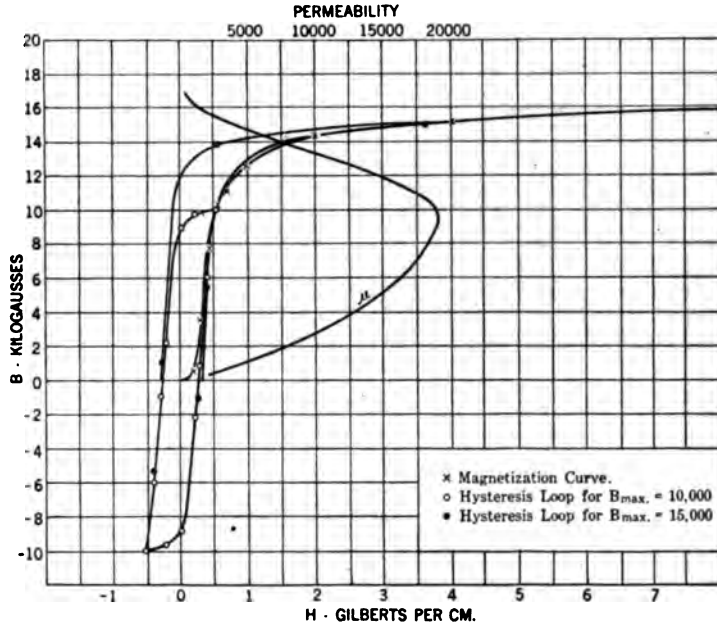


FIG. 10—HYSTERESIS LOOPS AND PERMEABILITY CURVE FOR ROD NO. 3-38, ANNEALED AT 900 DEG. CENT., COOLED IN 48 HOURS

about 4 per cent silicon. These two sets were supplied by the manufacturers and have received their standard anneal. They are supposed to represent good commercial steel used for electrical machinery. Table I also includes some information with regard to the properties of the electrolytic iron as melted in the resistance furnace. Figs. 11 and 12 show the magnetization curves for all the rods, compared with the average for the electrolytic iron melted in vacuo, all after having received the final heat treatment. The results of the mechanical tests are shown in Table II. A few of the photomicrographs are exhibited in

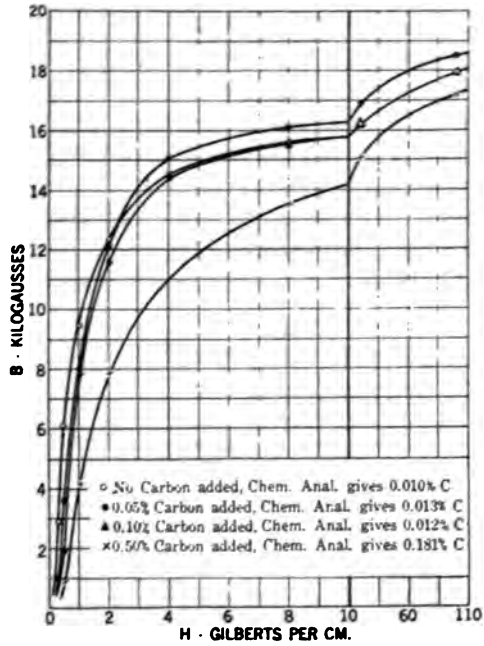


FIG. 11—MAGNETIZATION CURVES FOR THE IRON-CARBON ALLOYS, MELTED IN VACUO

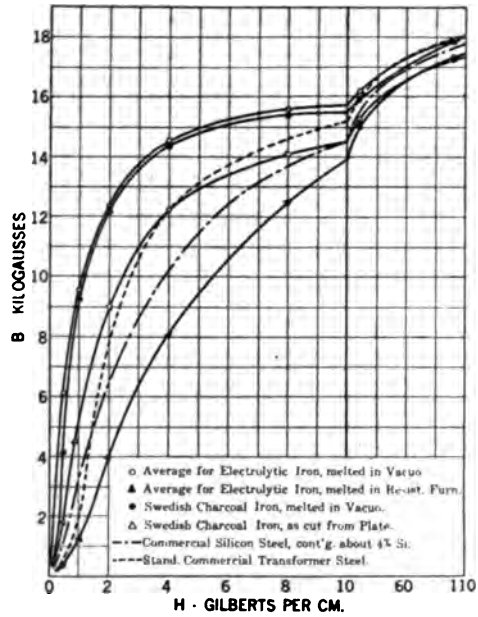
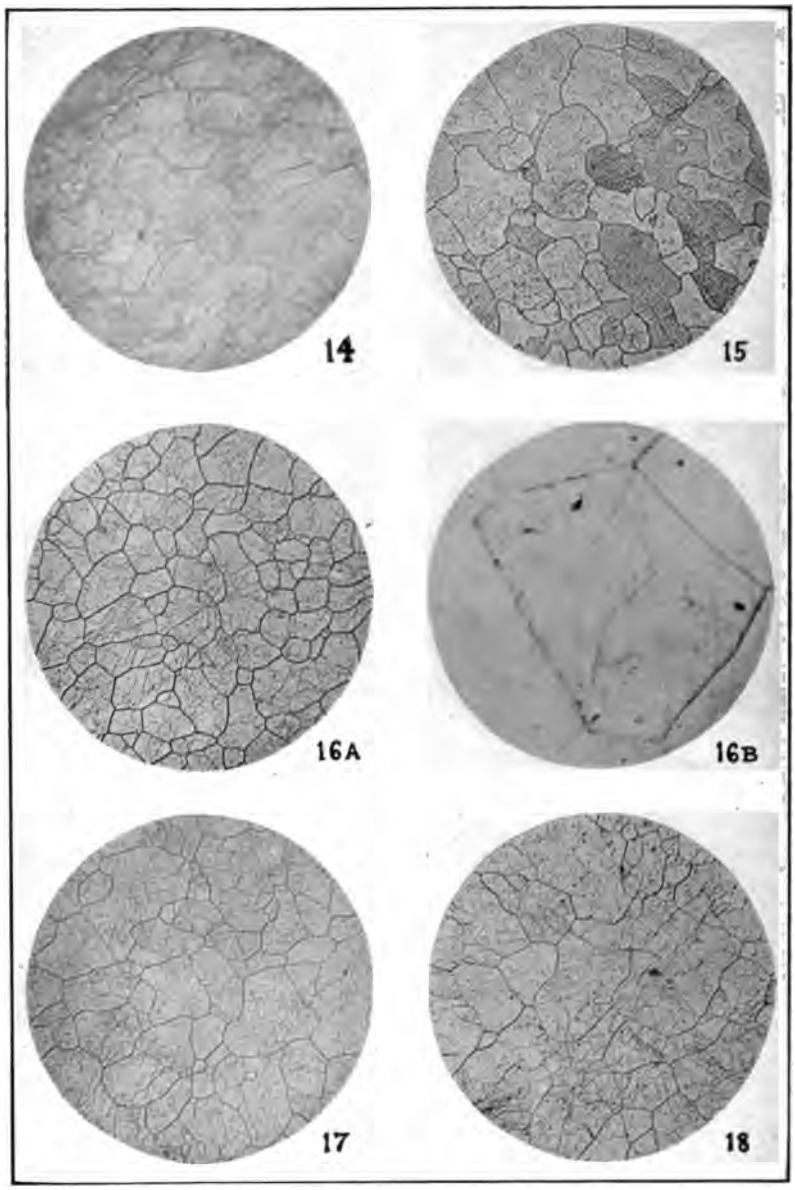


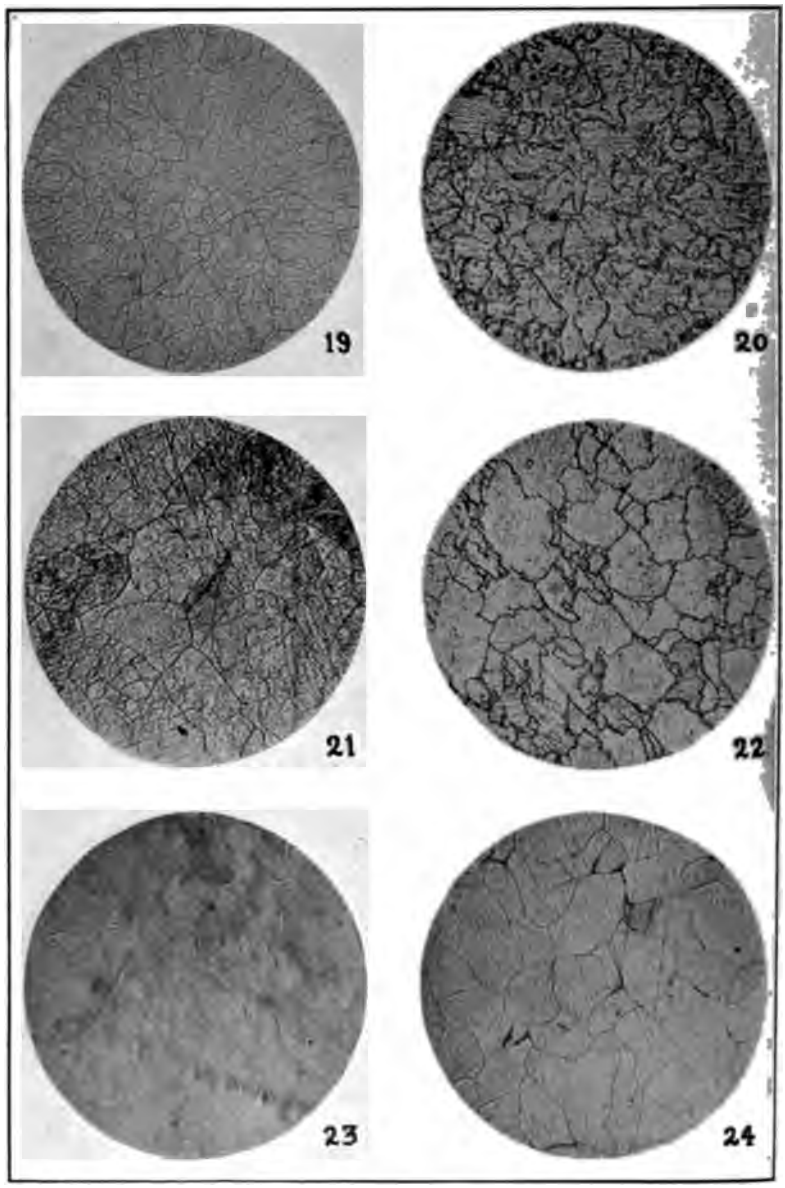
FIG. 12—COMPARISON OF MAGNETIZATION CURVES FOR DIFFERENT GRADES OF IRON



[YENSEN]

ELECTROLYTIC IRON MELTED IN VACUO

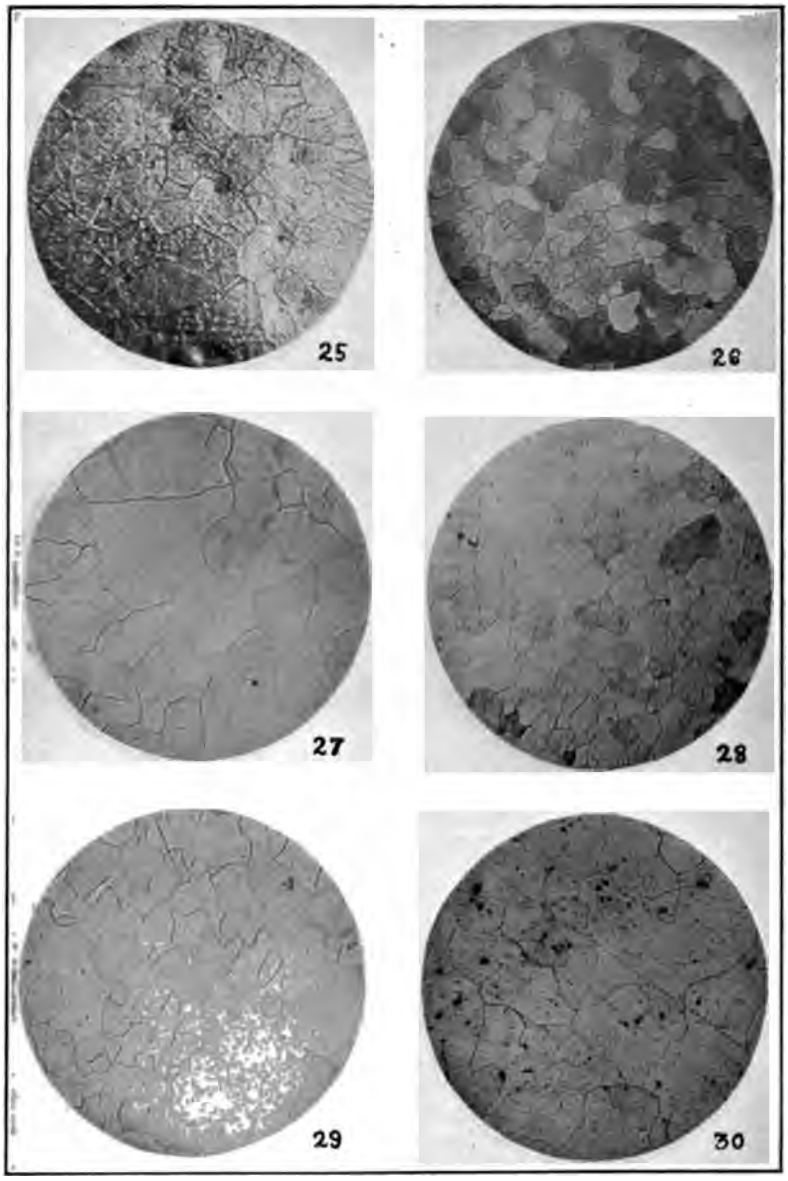
FIG. 14—No. 3-39B; annealed at 680 deg. cent. going up. 40 diam.
FIG. 15—No. 3-39D and E; annealed at 900 and 950 deg. cent. going up. 40 diam.
FIG. 16A—No. 3-39F; annealed at 1000 deg. cent. going up. 40 diam.
FIG. 16B—Same sample as in FIG. 16A, magnified 240 diam.
FIG. 17—No. 3-39G; annealed at 1060 deg. cent. going up. 40 diam.
FIG. 18—No. 3-39J; annealed at 800 deg. cent. going down. 40 diam.



[YENSEN]

ELECTROLYTIC IRON MELTED IN VACUO

FIG. 19.—No. 3-39L; annealed at 616 deg. cent. going down. **40 diam.**
FIG. 20.—No. 3-39O; quenched from 1000 deg. cent. in brine. **40 diam.**
FIG. 21.—No. 3-39S; annealed at 900 deg. cent., cooled in **48 hours. 40 diam.**
FIG. 22.—No. 3-31A; as forged. 40 diam.
FIG. 23.—No. 3-31K; annealed at 900 deg. cent., cooled in **48 hours. 40 diam.**
FIG. 24.—No. 3-36C; annealed at 900 deg. cent., cooled in **24 hours. 40 diam.**



[YENSEN]

FIG. 25—No. 3-38D, electrolytic iron melted in vacuo; annealed at 900 deg. cent., cooeld in 48 hours. 40 diam.

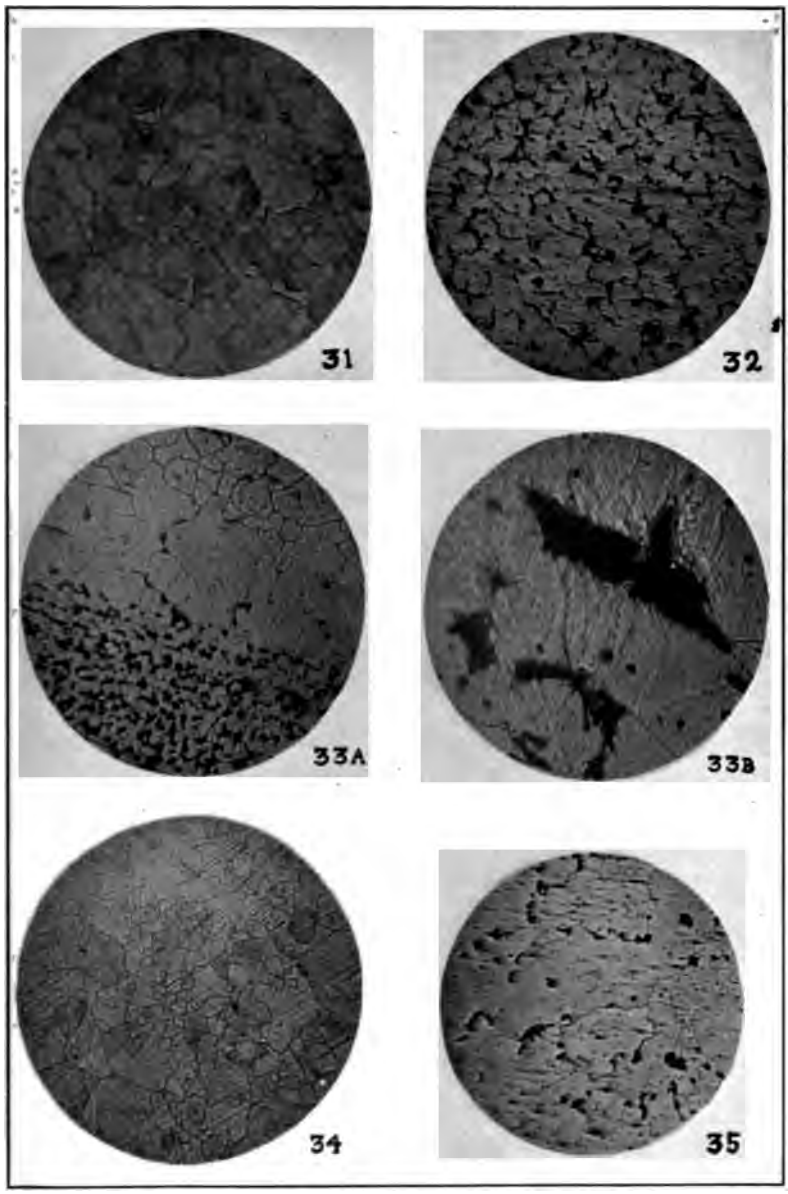
FIG. 26—No. 3-41B, electrolytic iron melted in vacuo; annealed at 900 deg. cent., cooled in 12 hours. 40 diam.

FIG. 27—No. 3-43B, electrolytic iron melted in vacuo; annealed at 900 deg. cent., cooled in 12 hours. 40 diam.

FIG. 28—No. 3-45B, electrolytic iron melted in vacuo; annealed at 900 deg. cent., cooled in 12 hours. 40 diam.

FIG. 29—No. 3-47B, electrolytic iron melted in vacuo; annealed at 900 deg. cent., cooled in 12 hours. 40 diam.

FIG. 30—No. 3C01D, electrolytic iron with 0.05 per cent carbon added, melted in vacuo; annealed at 900 deg. cent., cooled in 48 hrs. Analysis shows 0.013% carbon. 40 diam.



[YENSEN]

FIG. 31—No. 3C02D, electrolytic iron with 0.10 per cent carbon added, melted in vacuo; annealed at 900 deg. cent., cooled in 48 hours. Analysis shows 0.012 per cent carbon. 40 diam.

FIG. 32—No. 3C03D, electrolytic iron with 0.5 per cent carbon added, melted in vacuo; annealed at 900 deg. cent. Analysis shows 0.181 per cent carbon. 40 diam.

FIG. 33A—No. Sw. I-4B, Swedish charcoal iron cut from plate; annealed at 900 deg. cent. 40 diam.

FIG. 33B—Same sample as in FIG. 33A, magnified 240 diam.

FIG. 34—No. 1-21A, Swedish charcoal iron remelted in vacuo; as forged. 40 diam.

[illegible]—No. 3-13C, electrolytic iron melted in resistance furnace under atmospheric [illegible]; annealed at 900 deg. cent. 40 diam.

TABLE II.

Summary of Results of Mechanical Tests

Spec. No.	Carbon content %	A: As forged — Stress at yield point lb./sq. in.	A: Ultimate strength lb./sq. in.	A: Elong. % 1*	A: Elong. % 2†	A: Red'ct of area %	B: Annealed from 900° to 200° C. in 12 hr. accd. to straight line. — Stress at yield point lb./sq. in.	B: Ultimate strength lb./sq. in.	B: Elong. % 1*	B: Elong. % 2†	B: Red'ct of area %	C: Annealed from 900° to 200°C. in 24hr. acc'd. to log. curve exc. as noted — Stress at yield point lb./sq. in.	C: Ultimate strength lb./sq. in.	C: Elong. % 1*	C: Elong. % 2†	C: Red'ct of area %	D: Quenched in brine from 1000°C. except as noted — Stress at yield point lb./sq. in.	D: Ultimate strength lb./sq. in.	D: Elong. % 1*	D: Elong. % 2†	D: Red'ct of area %	Remarks
3-30	0.0090	36 600	44,800		41	87.7																
3-31	0.0120	69,100	70,500		20	82.8	20,700	35,500	30	60	89.5											
3-33		64,000	68,000		22	81.5												40,500	24	53	84.5	
3-34	0.0090												34,300		47	61.1		55,500	14	32	83.1	
3-35												14,400	34,500		54	87.3		44,900	22	44	86.0	
3-36	0.0150											20,100	37,500		52	77.0						
3-37	0.0450																41,250	64,600	15	37	73.7	
3-38	0.0104												35,150		56	85.5	37,400	45,500	17	42	86.1	
3-39	0.0110	35,800	44,700		39	80.4						16,400	36,100		61	80.9						Column C annealed in 48 hr. according to straight line.
3-40	0.0110	39,600	43,500		38	82.3		41,600		42	85.7											
3-41	0.0095	62,200	65,500		26	83.8		40,200	18	53	85.1											
3-43	0.0096						18,750	35,800	31	59	84.5											
3-45	0.0080	51,400	55,500		32	85.8	15,000	39,400	27	40	88											
3-47	0.0080						17,400	36,100	31	57	91.3						30,200	40,000	20	47	80.8	
																	15,500	35,400	27	45	36.6	Quenched in liq. air.
3-48	0.0080	45,600	51,800	12	36	86.4						15,300	35,800	23	42	73.2						Column C annealed 900° to 200° C. in 24hr. acc'd. to straight line.
3-49	0.0120	41,400	48,700	12	44	76.2						11,100	34,900	23	32	75.7						
3-50	0.0099	38,200		12.5	35							19,300	35,800	28	45	86.5						
Ave.	0.0125	48,390	54,800	12.2	33.3	83.0	17,960	38,100	27.4	51.8	87.4	16,100	35,500	24.7	48.6	78.4	36,280	50,170	18.6	42.5	82.4	
3C01	0.0130						21,000	51,100	27	41	72.5						33,200	53,000	20	65	86.2	% carbon added = 0.05
3C02	0.0120						19,400	38,900	29	60	73.5						67,700	76,900	7	25	79.7	" " " = 0.10
3C03	0.1810						22,100	51,000	24	50	64.5											" " " = 0.5
SwI-4	0.1630		40,000		36	57.0																As cut from plate.

*Elongation before specimen has commenced to "neck." † Ultimate elongation.

Figs. 13-34, including most of those obtained for rod No. 3-39, as this rod received more heat treatments than any other rod. This series for No. 3-39 may be studied to advantage in connection with Fig. 8. Figs. 30 to 32 show the effect upon the microstructure of adding carbon to the iron, and Figs. 33 and 34 show the difference between Swedish charcoal iron before and after being remelted in vacuo. The structure of the electrolytic iron melted in the resistance furnace is shown in Fig. 35. Fi-

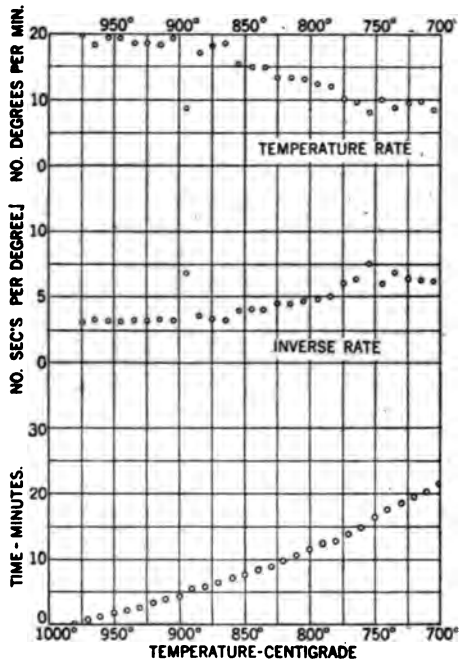


FIG. 36—COOLING CURVES FOR ROD NO. 3-43

nally, Fig. 36 is a sample cooling curve for the critical temperature determinations.

DISCUSSION OF RESULTS

The results obtained may perhaps best be discussed by considering first the equilibrium diagram for iron-carbon alloys. Fig. 37 shows this diagram as represented by Rozenhain.

This diagram should probably be modified somewhat in view of the recent researches upon the critical temperatures for pure iron. It has been shown, for instance, by Burgess and Crowe,

in a bulletin just issued by the Bureau of Standards, that the point *F*, usually called Ar_2, for pure iron is 768 deg cent. Furthermore, it has been shown conclusively that the temperature at which pure iron changes from a ferromagnetic to a paramagnetic substance or vice versa, is 785 deg. cent., thus showing that these two transformation points do not coincide.

Only that part of the diagram lying to the left of *I* will be considered here. From this diagram it is seen that after the iron has passed from the liquid state it exists in the form of a solid solution of iron and carbon, called austenite. When this solution cools it eventually reaches the line *E G I*, where ferrite crystals begin to be precipitated. Upon further cooling

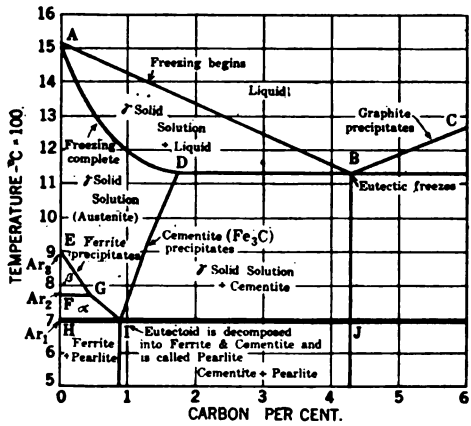


FIG. 37—EQUILIBRIUM DIAGRAM FOR IRON-CARBON ALLOYS, ACCORDING TO ROZENHAIN

the solution, now enriched in carbon, passes downwards towards the right, following *E G I*, more and more ferrite being precipitated. Finally, upon reaching the point *I*, the part of the solution still remaining, containing now 0.9 per cent carbon, is decomposed into cementite (Fe_3C) and ferrite, and the resulting mixture is called pearlite. At this temperature the iron consequently consists of pure ferrite crystals with the spaces between the crystals filled up with a mixture of ferrite and cementite. One generally-accepted theory states that iron has three different allotropic modifications: Alpha, Beta and Gamma. Gamma iron is stable above the line *E G I*, Beta iron between *E G* and *G F*, and Alpha iron below *G F*. It has been shown that iron in the

Beta and Gamma modifications is weakly paramagnetic, while Alpha iron is ferromagnetic. Under certain conditions Beta and Gamma iron may exist to some extent below the boundaries just stated. It is supposed, for instance, that if iron be cooled rapidly from a high temperature, Gamma and Beta iron may not have sufficient time to change into Alpha iron. If, however, such iron be reheated to above the line *E G I* and slowly cooled, the iron may ultimately all be obtained in the ferromagnetic Alpha modification. This theory is confirmed by the results obtained by Hadfield and Hopkinson, who found that the "specific magnetism" of iron-carbon alloys is decreased to a large but uncertain extent by quenching from a high temperature. Certain elements, carbon and manganese for example, when added to the iron assist in retaining the iron in the Gamma form. Thus Hadfield obtained an iron-manganese alloy that is practically non-magnetic at ordinary temperatures.

Another factor that may influence the magnetic properties of iron is mechanical strain, either due to outside influence or due to rapid cooling. It is not definitely known which is the more important, removing mechanical strain, or changing all the iron into Alpha iron. It is certain that both are important and that both may be accomplished by proper annealing. It is well known that if, subsequent to annealing, the iron be mechanically strained, its magnetic quality is depreciated. This point was confirmed by the writer while measuring a rod that had been slightly bent during the annealing process. Its permeability seemed, compared with previous measurements, to be unusually low. It was noticed that in clamping it in the permeameter it had been strained to some extent. It was then adjusted so as to lessen the strain as far as possible, and the permeability was found to have increased materially. This fact helped to explain some rather puzzling results previously obtained in the course of the investigation. It also showed that, if the iron has not been strained beyond a certain point, the effect of the strain is only temporary.

With the above explanations and facts in mind, the results given in the previous part of the paper will now be considered.

It is at once apparent from Table I that the melting of electrolytic iron, or low-carbon iron in general, in an atmosphere of carbon monoxide gases, gives the iron a chance to absorb carbon, the amount absorbed varying from 0.05 to 0.15 per cent. This result is in agreement with the experiments of Burgess and Aston

referred to in the introduction. It is furthermore seen that carbon is not the only factor that affects the magnetic properties of iron. Swedish charcoal iron, Sw.I-4, with a carbon content of 0.163 per cent, and 3C03, an electrolytic iron-carbon alloy melted in vacuo, with a carbon content of 0.181 per cent, both have a decidedly higher permeability than the electrolytic iron melted in the resistance furnace, although the latter has an average carbon content of only 0.10 per cent. Again, the electrical resistance of the resistance furnace iron is 13.52 microhms while that of Sw.I-4 and 3C03 is 10.57 and 12.40 respectively. The carbon content of 0.1 per cent does not by itself account for a resistance of 13.52 microhms. According to Barrett this resistance corresponds to a carbon content of 0.6 per cent. As carbon is probably absorbed from CO according to the reversible reaction

$$Fe + CO \rightleftarrows FeO + C$$

it seems natural to assume that not only carbon but also FeO is absorbed by the iron. In that case the result would be an alloy of ferrite, cementite (Fe_3C) and iron oxide (Fe O). For a carbon content of 0.1 per cent the alloy would contain 1.5 per cent cementite, and 0.59 per cent FeO. While cementite is slightly ferromagnetic, as shown by Hadfield and Hopkinson, FeO is paramagnetic, and a very poor conductor of electricity. With these two substances interspersed among the ferrite crystals, the low permeability and high resistance can be satisfactorily explained. From a further study of Table I it is seen that the Swedish charcoal iron has lost nearly all of its carbon by being melted in vacuo, the carbon content in the final iron being only 0.008 per cent. At the same time, as would be expected, its electrical resistance has been slightly lowered and its magnetic permeability considerably increased. Similarly, the three iron-carbon alloys melted in vacuo, 3C01, 3C02 and 3C03, have lost the larger part of the carbon added to them. While the additions amounted to 0.05, 0.10 and 0.50 per cent respectively, the chemical analysis of the final rods shows a carbon content of 0.013, 0.012 and 0.181 per cent. If to the former figures be added the carbon content of the electrolytic iron as deposited, namely 0.006 per cent, the loss of carbon is found to be 76.8, 80.5 and 64.4 per cent respectively. The corresponding loss for the Swedish iron was 95 per cent. The Bureau of Standards has demonstrated that such a loss occurs by melting electrolytic iron in vacuo, the loss

found being in one case 67 per cent, in another case 87.5 per cent. In the present case the electrolytic iron melted in vacuo not only did not lose any carbon, but actually gained a slight amount. In order to explain this apparent discrepancy it should be mentioned that the pressure used by the Bureau of Standards investigators in their vacuum furnace was 0.01 mm. of mercury, while the pressure used by the writer was from 2 to 5 mm. Based upon the facts above enumerated, the following explanation is now offered. Any oxygen left in the furnace combines with the carbon of the heating element and forms carbon monoxide (CO). This gas, as already stated in connection with the results obtained with the resistance furnace, reacts with the iron according to the reversible equation

$$Fe + CO \rightleftarrows FeO + C$$

until equilibrium is established. If now the pressure in the furnace be lowered the reaction will take place from right to left; that is, any FeO that may be present will be reduced by the carbon in the iron, with the result that the carbon content will be reduced until equilibrium is restored. Conversely, with an increase of pressure due to an admission of oxygen, the reaction will take place from left to right, and the carbon content, as well as the FeO, of the iron will be increased. Upon this hypothesis the difference between the carbon content obtained by the Bureau of Standards and that obtained by the writer is immediately explained.

The changes in the structure of the Swedish iron are very well illustrated by the photomicrographs shown in Figs. 33A and 33B and Fig. 34. Fig. 33A shows the non-homogeneous Swedish iron as rolled. The dark spots are probably partly slag and partly pearlite, shown to a higher magnification in Fig. 33B. Fig. 34 shows the iron after being melted in vacuo, being perfectly homogeneous and without any sign of pearlite. Figs. 30 to 32 show the structure for the iron-carbon alloys 3C01, 3C02 and 3C03, verifying in general the chemical analysis as to carbon content. By referring to Fig. 11 and Table I, it is seen that the electrical resistance and magnetic permeability for these iron-carbon alloys are not strictly in accordance with the chemical analysis. From the latter, 3C01 and 3C02 are approximately alike, while the electrical and magnetic tests indicate that 3C02 should have a higher carbon content than 3C01. Why this discrepancy should

exist is difficult to explain, as the analysis for 3C02 was repeated four times, giving results that agreed quite closely.

The effect of annealing at different temperatures is shown graphically in Fig. 8. From this figure it is seen that the permeability increases quite uniformly as the annealing temperature is raised, at first slowly, and then very rapidly as the annealing temperatures are raised from 700 to 800 deg. cent. Above 900 deg. cent. some uncertainty appears. The permeability is decreased for 950 deg. and again increased for 1000 deg. cent' Whether this result is due to mechanical strain in clamping the rod in the permeameter or whether it is due to different rates of cooling or to some other cause, the writer is not prepared to say. From the experience previously related it seems most probable that the drop for 950 deg. is due to mechanical straining, as it occurs for low values of H only. The experiments of Terry show that 1100 deg. cent. is the most favorable annealing temperature for pure iron. While the results shown in Fig. 8 are not conclusive in themselves, they help to confirm the results obtained by Terry. Another interesting point is shown in Fig. 8. For values of $H = 8$, or above, the permeability is decreased by annealing at temperatures above 900 deg. cent., and does not return to the higher value by further annealing at lower temperatures. Furthermore, upon annealing successively at decreasingly lower temperatures, the permeability is increased for low values of H. Such a process is, of course, equivalent to annealing at the highest temperature and cooling at a slower rate than was used for each of the successive annealings. This assumption was verified by annealing at 900 deg. cent. and cooling, first in 24 hours according to a logarithmic time-temperature curve, and finally in 48 hours according to a straight line connecting 900 and 200 deg. cent. These treatments increased the permeability considerably for low values of H, but did not alter it for high values of H. Quenching from 1000 deg. cent. in iced brine produced a decidedly magnetic hardening, but this hardening was again removed by reheating to 900 deg. cent. and slow cooling.

The results obtained with rod No. 3-39 are confirmed by those obtained with the three groups of rods made from electrolytic iron melted in vacuo. Thus, the rods of group 2, including Nos. 3-34, 3-36, 3-37 and 3-38, that were reheated to forging temperature, between 1000 and 1100 deg. cent., give a decidedly lower permeability for high values of H than rods that have not been heated above 900 deg. cent. The same is shown by the results

obtained for the rods of group 4, including Nos. 3-48, 3-49 and 3-50, after these rods had been annealed at 1080 deg. cent. Whether annealing at temperatures above 900 deg. cent. improves the permeability for low values of H has not been definitely demonstrated by this investigation. As was mentioned above, Terry has shown that 1100 deg. cent. is the most favorable annealing temperature for electrolytic iron as deposited, as this gave a lower hysteresis loss than annealing at lower temperatures. To be sure, the rods belonging to group 2, as well as rod No. 3-39, that some time during the process were heated above 1000 deg. cent., include the best rods magnetically of the entire series.[7] But the rods of group 4 were not improved materially by annealing at 1080 deg. cent. after having previously been annealed at 900 deg. cent.

The average magnetization curve for electrolytic iron melted in vacuo, as shown in Figs. 11 and 12, is based upon the results obtained after the final heat treatment, whether this gave the best results for each particular rod or not. This average also includes the results for rod No. 3-37, that perhaps should have been thrown out. The average curve is, therefore, somewhat lower than might be expected for 15 rods treated under more favorable conditions. However, it serves to indicate the place occupied by electrolytic vacuum iron, in relation to other grades of iron.

While the curve for the electrolytic vacuum iron is the highest of those represented in Fig. 12, the curve for the Swedish charcoal iron remelted in vacuo is a close second, and these two are far above the curves for commercial iron used at present for magnetic purposes. The maximum permeability for the average magnetization curve, as shown by Table I, is 12,950, occurring at a flux density of 6550 gausses. The maximum obtained, however, is 19,000 for rod No. 3-38, at a flux density of 9500 gausses.

Terry gives 11,000 as the maximum permeability obtained for electrolytic iron as deposited, but it is not perfectly clear whether this permeability occurred at ordinary temperatures or in the neighborhood of 760 deg. cent., as he compares this maximum value obtained with that obtained by Morris (15,000) and that obtained by Wells (17,000), both of which occurred at very low

7. Rod No. 3-37 has an exceptionally low permeability but this rod had probably had an accident sometime, as the chemical analysis shows that it contains 0.045 per cent carbon.

flux densities and near the critical temperature, 785 deg. cent. However, it is believed that Terry's maximum occurred at room temperature after annealing at 1100 deg. cent.

While high permeability is of interest for certain purposes, the characteristics of iron that are of special interest to the manufacturer and user of electrical machinery are hysteresis and eddy current losses, the latter depending largely upon the electrical resistance of the iron.

From Table I the hysteresis loss for B_{max} = 10,000 is seen to be less than one-half as high for the average electrolytic vacuum iron as it is for the commercial silicon steel, while for B_{max} = 15,000, the corresponding figure is about two-thirds. The reason why the hysteresis loss for the vacuum iron is not even still lower, compared with commercial iron, is readily seen by looking at the figures for retentivity. (See also Fig. 10). While the retentivity for B_{max} = 15,000 is 9940 for the average electrolytic vacuum iron, it is only 5400 for silicon steel. The hysteresis loss for Hadfield's best magnetic steels, the 2½ per cent silicon alloy and the 2¼ per cent aluminum alloy, as reported by Barrett, Brown and Hadfield, for B_{max} = 9000 is 1550 and 1440 ergs, respectively, per cu. cm. per cycle. Comparing these results, it is seen that in spite of the high retentivity, the hysteresis loss for the electrolytic vacuum iron is much lower than for any material thus far produced, of which the literature gives information. This is due to the low coercive force, namely, 0.34 gilbert per cm., this being the average value for the 15 rods.

The electrical resistance for the average vacuum iron is 9.96 microhms per cm. cube. The resistance for the standard transformer steel is 11.09 microhms, while that for the silicon steel is 51.15 microhms. Thus the eddy current losses per unit volume, for the same thickness of sheet and for the same maximum flux density, would be much in favor of the silicon steel. However, it is definitely known that the resistance of the latter can be raised by the addition of silicon or aluminum. What the effect of such additions upon the magnetic quality of the iron will be, remains to be seen, but judging from the effect they have upon commercial grades of iron, it seems probable that it will not be harmful.

While the photomicrographs are of interest primarily as showing the structure of electrolytic vacuum iron in general, and in what respects it differs from other grades of iron, certain conclusions as to the relation between the microstructure and

the magnetic quality of the iron may be drawn. Considering the series for rod No. 3-39, it appears that there is no general growth in the size of crystals. Annealing above 900 deg. cent., with subsequent slow cooling, breaks the crystals up into smaller parts. Quenching from 1000 deg. cent., this fine structure again gives way for larger crystals with indefinite boundaries, but the fine structure reappears upon subsequent annealing and slow cooling. The structure that seems to give the best magnetic quality is that shown in Figs. 19 and 21 for rod No. 3-39. This same structure is obtained for the best rod of the series, No. 3-38, as shown in Fig. 25, and for No. 3-31, in Fig. 23. The results of the critical temperature determinations show that the point Ar_3 (see Fig. 37) for the average electrolytic vacuum iron is 894 deg. cent., agreeing with the value found by the Bureau of Standards for pure iron.

Table II shows that magnetic and mechanical hardness go together, and serves to confirm further the results obtained by previous writers. It emphasizes the extreme mechanical softness of the electrolytic iron melted in vacuo, particularly after annealing at 900 deg. cent. In comparing Nos. 3C01, 3C02 and 3C03 with the rest of the rods, it should be remembered that the actual carbon content of these rods is 0.013, 0.012 and 0.181 per cent, respectively.

Summary and Conclusion

The results recorded in the previous pages may be summarized as follows:

1. Pure iron melted in an atmosphere of carbon monoxide, under atmospheric pressure, will absorb both carbon and oxygen, with the result that the iron thus produced is of an inferior magnetic quality.

2. Low-carbon iron melted in vacuo will lose 50 to 90 per cent of its original carbon content.

3. The magnetic quality of electrolytic iron melted in vacuo is decidedly superior to any grade of iron thus far produced, the maximum permeability obtained being 19,000 at a flux density of 9500 gausses. The average hysteresis loss obtained is less than 50 per cent of that found in the best grades of commercial transformer iron.

4. The specific electrical resistance of pure iron melted in vacuo is 9.96 microhms.

5. Swedish charcoal iron melted in vacuo has a magnetic

quality approximating that of electrolytic iron melted in vacuo, chiefly due to the reduction of the carbon content.

From these facts it appears that a superior quality of iron for magnetic purposes may be obtained by melting electrolytic iron in vacuo. While the electrical resistance of the iron thus obtained is very low, this defect may be remedied by the addition of such alloying elements as silicon or aluminum, elements that are known to increase the electrical resistance very materially without affecting the magnetic quality to any large extent. Experiments are now under way for determining the effect of such alloying elements, and the results will be published at some later date.

Whether iron melted in vacuo will ever become a commercial product depends, of course, upon whether any apparatus can be devised for producing such iron on a commercial scale at a cost that will not be prohibitive.

In conclusion, the writer wishes to acknowledge his indebtedness to a large number of persons connected with various departments of the University of Illinois, who have rendered valuable assistance in carrying on this investigation.

A number of large manufacturing companies have also shown their willingness to cooperate in the work, by going to great trouble and expense in preparing rods from commercial grades of iron.

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SOLENOIDS

BY CHARLES R. UNDERHILL

ABSTRACT OF PAPER

Maxwell's law for the attraction between the halves of a bar electromagnet is not correct for electromagnets of the plunger type with air gaps between the cores because the flux in the cores is, to a large extent, independent of the reluctance in the air gap on account of the magnetic leakage from the inner end of either core back to the other end of the same core.

In this paper, only the characteristics of direct-current electromagnets are discussed. An attempt is made to show the correct law of attraction for tractive electromagnets and to calculate the value of the magnetizing force at any point along the axis of any solenoid. Test characteristics are given to support the theories.

The work done by an electromagnet of the plunger type in closing its air gap is largely proportional to the length of the air gap, although, when the reluctance of the air gap and the total m.m.f. are of low value, the law of Carichoff is approximately correct for the total attraction.

THE EXTENSIVE use of electromagnets of the plunger type has caused the details of their design to become increasingly important. They are frequently divided into two classes; viz. long-range and short range. The equations in common use for calculating the static pulls due to short-range electromagnets, while more or less satisfactory for relatively short air-gaps, since the pulls are usually greater than calculated, are not applicable for predetermining the pulls when the air gaps are relatively long. In this paper, the static pull is always meant.

A general equation is desirable, by means of which the pulls may be predetermined for any type of movable-core electromagnet, whether or not it is provided with either a frame or stop, or both. Such an equation would be applicable to electromagnets designed to operate on either alternating or direct currents, after the mean effective values of the m. m. fs. which produce the pull had been determined at points throughout the range of travel of the plunger. The shapes of the mean effective pull curves for alternating-current electromagnets would naturally differ from those for direct current, owing to the different values of the m.m.fs. at corresponding points throughout the range of

travel, but the general law for the mean effective pull for a given m.m.f. would be the same in both cases, after making corrections for iron losses.*

In this paper, only the characteristics of direct-current electromagnets are discussed. The voltage across the windings and the current strength are assumed to be at constant value, in any given case, and the plungers are assumed to be at rest; so that it is not necessary to consider the effects of self-induction which are in evidence in alternating-current electromagnets and also in those operating on direct current when the plunger is in motion.

The fundamental equation of Maxwell,

$$P_s = \frac{B^2}{8\pi} \tag{1}$$

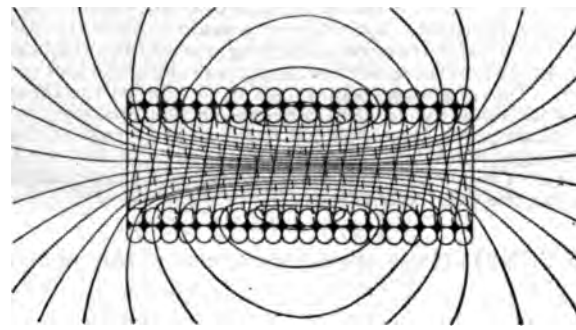

FIG 2—MAGNETIC FIELD OF SOLENOID

for the attraction in dynes per sq. cm., does not apply, either directly or tacitly, to the case of a solenoid-and-plunger only, or to plunger electromagnets with relatively long air gaps.

The familar analysis of Maxwell's equation is here given. The magnetic induction B consists of two components, $4\pi I$ (I being the intensity of magnetization in the iron) and the magnetizing force H. Hence

$$B = 4\pi I + H \tag{2}$$

Substituting (2) in (1),

$$P_s = 2\pi I^2 + I H + \frac{H^2}{8\pi} \tag{3}$$

*See "Alternating-Current Electromagnets," *Electrical World*, Vol. 63, No. 5, p. 260 (1914).

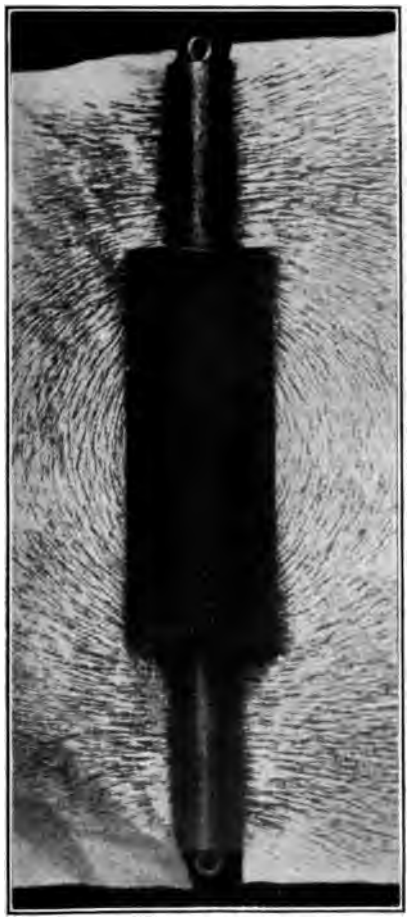

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FIG. 1—MAGNETIC FIELD OF BAR ELECTROMAGNET WITHOUT INTERNAL AIR-GAP

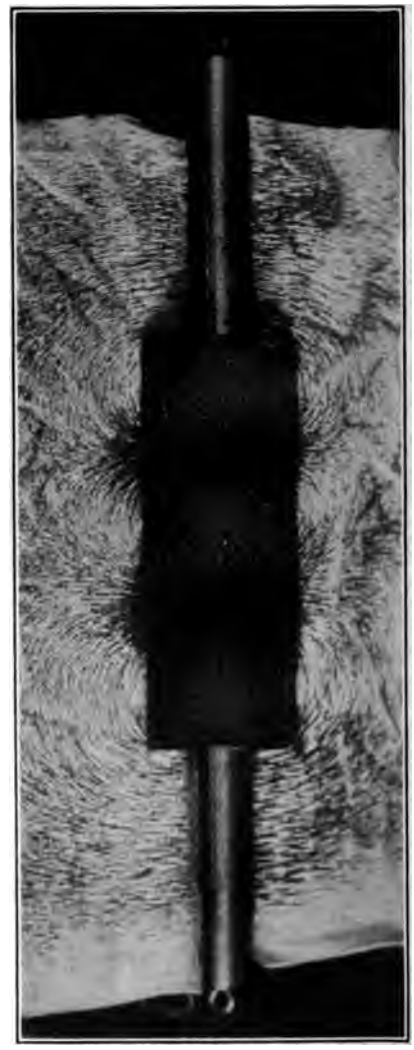

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FIG. 5—MAGNETIC FIELDS WHEN AIR-GAP IS INTRODUCED

which is the equation for the attraction in dynes per sq. cm. between the two halves of a bar electromagnet separated at its middle at right angles to the axis of the core, but perfectly joined magnetically; hence there is assumed to be no leakage from the

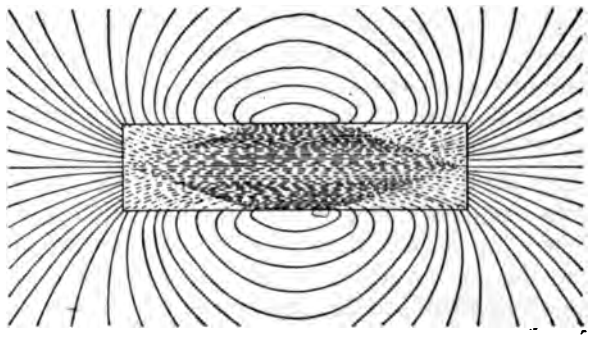


FIG. 3—FIELD OF BAR PERMANENT MAGNET

ends of the abutting half-cores back to the opposite end of the same half-core, as shown in Fig. 1.

Conventionally stated, the attraction between the ends of the iron half-cores is $2\pi I^2$; IH is the attaction between the half-coil

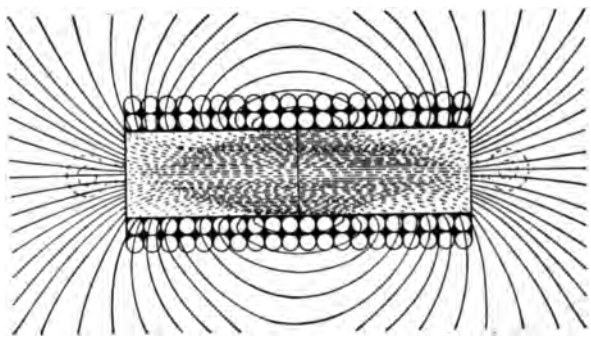


FIG. 4—BAR ELECTROMAGNET WITH DIVIDED CORE

and half-cores, and $\frac{H^2}{8\pi}$ is the attraction between the half-coils, which is not available in a single coil as commonly used in practise and is, therefore, neglected.

In Figs. 2 and 3 are shown the fields of a solenoid and a bar permanent magnet respectively. The following assumptions apply to Fig. 4, which shows the field of a practical bar electro-

magnet: The core is cut across at the middle but the joint is as perfect magnetically as though the structure were solid; the coil is uniformly wound in layers; the complete core fits closely inside of the coil, but either half can be moved, without friction, along the horizontal axis of the coil.

When spring balances are attached to the protruding ends of the half-cores, and the coil "floats" around the complete core, the pull required to separate the two half-cores is $2\pi I^2+IH$, since the coil is not divided. Now, as soon as the two half-cores are separated, Maxwell's law no longer holds, because what before was a single electromagnet has now become the equivalent of three electromagnets. This is clearly shown in Fig. 5. Each half-core now has a field like that of the permanent magnet in Fig. 3, and the air gap has a similar magnetic field. The total m.m.f. is now divided into three components, so far as the conditions inside of the core of the coil are concerned, and this is the

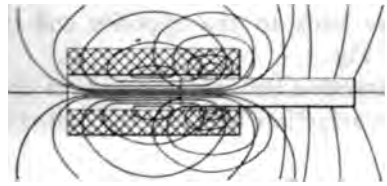


FIG. 6—PLUNGER ONE-THIRD IN SOLENOID

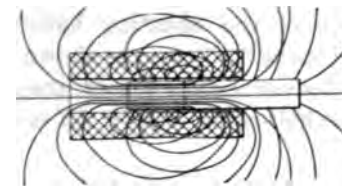


FIG. 7—PLUNGER TWO-THIRDS IN SOLENOID

basis of the doctrine of the effects of magnetic leakage in electromagnets of the plunger type, which is of great importance in continuous-current electromagnets but of paramount importance in alternating-current electromagnets.

Figs. 6 and 7 show the conditions which exist when a single core or plunger is inserted different distances within the coil. The density of the flux within the solenoid is assumed to be always the same at a given point, and is greatest at the middle of the coil along the horizontal axis. The position of maximum structural flux density of the plunger is always, approximately at least, half way between the inserted end of the plunger and the end of the coil at which the plunger enters. This is apparent in Fig. 5. When the middle of the plunger is at the middle of the coil, the two magnetic fields coincide and force is required to move the plunger in either direction.

When two plungers are placed within the solenoid, as in Figs.

5 and 8, spring balances are attached to the protruding ends, and the balances moved in the direction of the arrows, with the coil "floating" on the plungers, the pull as measured on either balance is the total pull which can be obtained with either plunger, since one pull is active and the other is reactive. The coil merely acts as a connecting link between the plungers. There is, how-

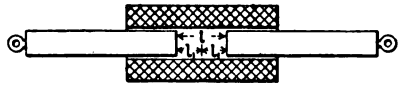


FIG. 8—SOLENOID WITH TWO PLUNGERS

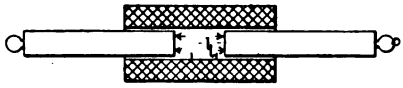


FIG. 9—SOLENOID WITH ONE PLUNGER FIXED IN POSITION

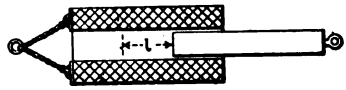


FIG. 10—ONE OF THE PLUNGERS IS OMITTED

ever, some attraction between the ends of the plungers, but this is slight when the air gap is so long. Therefore, omitting the attraction between the inner ends of the plungers, it makes no difference whether the conditions are as in Fig. 8; in Fig. 9, wherein one plunger is rigidly fastened to the coil, or as in Fig. 10, wherein one of the plungers is omitted entirely.

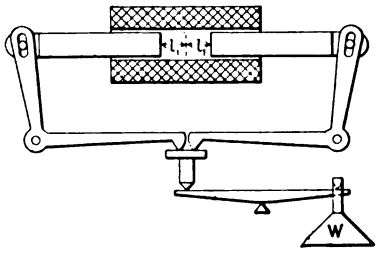


FIG. 11—BOTH PLUNGERS WORKING TOGETHER

In any case, the attraction that draws the plunger within the coil is the product of the average intensity of magnetization within the structure of the plunger and the average magnetizing force within the solenoid. This is found true by actual test and can be proved on the principle of work by assuming the pull to be constant throughout the range or distance of travel of the plunger. In Fig. 8, either plunger, when acting separately, can do $p\,l$ units of work, wherein p is the pull. The same holds true for the conditions in Figs. 9 and 10. When both plungers act together, the work done is $2\,p\,l_1$, as illustrated in Figs. 8 and 11, but the work done in both cases is the same. In Fig. 11, the two plungers can

lift the weight W equal to $2p$, but only through a distance l_1, which is equal to $\frac{l}{2}$. Hence the attraction or pull between a solenoid and plunger is

$$P_s = I H \tag{4}$$

The magnetizing force at the center of a solenoid whose length is great as compared with its average radius is

$$H = \frac{0.4\,\pi\, i\, n}{L} \tag{5}$$

wherein i is the current in amperes, n is the number of turns in the solenoid, and L is the length of the solenoid in cm.

The magnetizing force at any point on the horizontal axis of any uniformly wound solenoid is

$$H = \frac{0.2\,\pi\, i\, n\, h}{L} \tag{6}$$

wherein h is the coefficient of magnetizing force which is proportional to the length and average radius of the solenoid.

Let

$$\frac{\phi_i}{S} = 4\,\pi\, I \tag{7}$$

wherein ϕ_i is the structual flux in the plunger and S is the cross-sectional area of the plunger in sq. cm.

Then

$$I = \frac{\phi_i}{4\,\pi\, S} \tag{8}$$

Substituting (6) and (8) in (4),

$$P_s = \frac{\phi_i\, i\, n\, h}{20\, S\, L} \tag{9}$$

The pull in dynes is

$$P_d = P_s\, S \tag{10}$$

Substituting (**10**) in (**9**),

$$P_d = \frac{\phi_i\, i\, n\, h}{20\, L} \tag{11}$$

The attraction in kg. is

$$P = \frac{\phi_i\, i\, n\, h}{20 \times 981{,}000\, L} = \frac{\phi_i\, i\, n\, h}{19{,}620{,}000\, L} \tag{12}$$

The *approximate* values of the coefficient of magnetizing force h are found in the manner described below. The solenoid is assumed to be in the form of a hollow cylinder and to consist of a series of helices of conducting material wound at right angles to the horizontal axis. The method is based on the well-known equation for the magnetizing force H due to a single turn of the conductor in which current is flowing, as measured along the horizontal axis of the turn.

The expression is

$$H = \frac{0.2\, \pi\, i\, r^2}{(r^2 + x^2)^{\frac{3}{2}}} \tag{13}$$

wherein r is the average radius of the conductor as measured from the horizontal axis to the center of the cross-section of the conductor, and x is any point on the horizontal axis in either direction, as measured from the vertical axis; r and x are measured in cm.

S. P. Thompson* has shown a graphical method for determining the values of H along the horizontal axis of a solenoid, which consists of plotting the H curve for each turn and then adding the ordinates of all of the curves together. The first curve is due to a single turn, while the adjacent curve represents the magnetizing force due to a second turn, one centimeter from the first, plus that due to the first turn. This general idea is carried out throughout the rest of the figure. Both sides of each curve are exactly similar. Taking the maximum value of H for a single turn as unity, the maximum value of H at the middle of a solenoid consisting of an infinite number of turns would be two.

For the purpose of this paper, the values of h have been cal-

*"The Electromagnet," p. 248.

culated for certain points, and curves drawn through these points from which any value of H may be found. The method consists of dividing the length L of a solenoid by its average radius r and designating the quotient, or the number of sections, by m; each section being considered in the same manner as each single turn in the method described above.

Then

$$m = \frac{L}{r} \tag{14}$$

The magnetizing force at the center of any one section without any other section near it is

$$H_c = \frac{0.2\,\pi\,i\,n_s}{r} \tag{15}$$

wherein n_s is the number of turns in one section.

At any distance x, as measured in section-lengths on the horizontal axis from the center of the section,

$$H_c = 0.2\,\pi\,i\,n_s \frac{r^2}{(r^2 + x^2)^{\frac{3}{2}}} \tag{16}$$

Let

$$q = \frac{r^2}{(r^2 + x^2)^{\frac{3}{2}}} = \frac{H_c}{0.2\,\pi\,i\,n_s} \tag{17}$$

and

$$h_a = q\,r \tag{18}$$

Then at any distance x on the horizontal axis, from the center of the section,

$$h_a = \frac{r^3}{(r^2 + x^2)^{\frac{3}{2}}} \tag{19}$$

while at the center of the section, $h_a = 1$

But

$$x = r\,m_s \tag{20}$$

wherein m_s is the distance in section-lengths from the center of the section.

Therefore

$$h_a = (1 + m_s^2)^{-\frac{3}{2}} \tag{21}$$

Let a represent the section of reference, m_r the number of sections to the right of a, and m_l the number of sections to the left of a. (See Fig. 12).

Then

$$h = \sum_{1}^{m_r} h_s + \sum_{1}^{m_l} h_s + 1 \tag{22}$$

That is, h represents the sum of all of the values of $\frac{H_c\, r}{0.2\, \pi\, i\, n_s}$ at the center of the section of reference.

The equation for h at the center of either end-section may also be expressed

$$h = \sum_{1}^{m-1} h_s + 1 \tag{23}$$

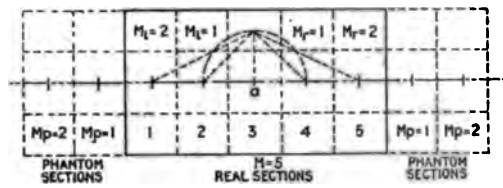


FIG. 12

For points outside of the solenoid, on the horizontal axis, at the center of any " phantom " section,

$$h = \sum_{m_p}^{m+m_p-1} h_s \tag{24}$$

wherein m_p is the number of the phantom section.

Likewise the value of h at points midway between the centers of the sections may be found by an equation

$$h = \sum_{.5}^{m_r-.5} h_s + \sum_{.5}^{m_l-.5} h_s \tag{25}$$

wherein m_r and m_l are the number of whole sections to the right or left, respectively, from the chosen points of reference.

The equation for the phantom sections, or those points outside of the solenoid, is

$$h = \sum_{m_p-.5}^{m+m_p-.5} h_s \tag{26}$$

Substituting (**17**) and (**18**),

$$h_a = \frac{H_c\, r}{0.2\, \pi\, i\, n} \tag{27}$$

By definition

$$h = \Sigma\, h_a \tag{28}$$

Therefore

$$h = \frac{H\, r}{0.2\, \pi\, i\, n_s} \tag{29}$$

whence

$$H = \frac{0.2\, \pi\, i\, n_s\, h}{r} \tag{30}$$

The number of turns of conductor in one section is

$$n_s = \frac{n}{m} \tag{31}$$

wherein n is the total number of turns in the solenoid and m is the number of sections.

Substituting (**14**) and (**31**) in (**30**),

$$H = \frac{0.2\, \pi\, i\, n\, h}{L} \tag{6}$$

When h reaches its maximum value of 2, as in a solenoid whose length is great as compared with its average radius, the magnetizing force at the center is

$$H = \frac{0.4\, \pi\, i\, n}{L} \tag{5}$$

In Table I, the column marked m_s represents the number of sections from the section of reference a as measured in either direction. The section of reference is not counted. The column h_a indicates the values corresponding to m_s as calculated by equation (**21**), while in the column marked $\sum_1^{m_s} h_a$ are given the sums of h_a corresponding to the values of m_s. The value of h_a for the section of reference is one. It is seen that the series of h_a converges rapidly.

TABLE I. Values of h.

m_s	h_a	$\sum_1^{m_s} h_a$	$\sum_2^{m_s} h_a$	$\sum_3^{m_s} h_a$	$\sum_4^{m_s} h_a$	$\sum_5^{m_s} h_a$	$\sum_6^{m_s} h_a$	$\sum_7^{m_s} h_a$	$\sum_8^{m_s} h_a$	$\sum_9^{m_s} h_a$	$\sum_{10}^{m_s} h_a$	$\sum_{11}^{m_s} h_a$
1	.354	.354										
2	.089	.443	.089									
3	.0316	.475	.121	.032								
4	.0143	.489	.135	.046	.014							
5	.00754	.496	.143	.053	.022	.0075						
6	.00444	.501	.147	.058	.026	.012	.0044					
7	.00283	.504	.150	.061	.029	.015	.0073	.0028				
8	.00191	.506	.152	.063	.031	.017	.0092	.0047	.0019			
9	.00135	.507	.153	.064	.032	.018	.0105	.0061	.0033	.0014		
10	.000985	.508	.154	.065	.033	.019	.0115	.0071	.0042	.0023	.00098	
11	.000742	.509	.155	.066	.034	.020	.0123	.0078	.0050	.0031	.00173	.00074
12	.000573	.509	.156	.066	.035	.020	.0128	.0084	.0056	.0036	.00230	00132

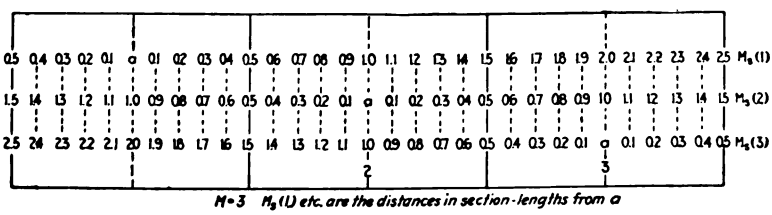
In Table II, which shows the values of h, m is the total number of sections in the solenoid and a is the number of the section of reference as counted from either end of the solenoid; 1 is an end-section; 2, 3, 4, 5 and 6 are middle sections when m is 3, 5, 7, 9 and 11 respectively.

TABLE II. Values of h.

Sec. of Ref. a / m	1	2	3	4	5	6
1	1.000					
2	1.354					
3	1.443	1.707				
4	1.475	1.797				
5	1.489	1.828	1.886			
6	1.496	1.842	1.918			
7	1.501	1.850	1.932	1.949		
8	1.504	1.854	1.939	1.964		
9	1.506	1.857	1.944	1.971	1.978	
10	1.507	1.859	1.947	1.976	1.985	
11	1.508	1.861	1.949	1.978	1.990	1.993

With 11 sections, the limit two at the center of the solenoid is approximated. If any solenoid be bent into the form of a ring, h will have a value of two at any point along what was formerly its horizontal axis.

Table III is similar to Table I but shows the values of h for points midway between the centers of the sections. Fig. 13 shows the method of finding the values of h at other points between the centers of the sections. In this figure, $m = 3$.



$M=3$ $M_3(1)$ etc. are the distances in section-lengths from a

FIG. 13

The curves marked h in Figs. 14 to 24 inclusive have been prepared from the above equations and tables. The peaks of the h curves in Figs. 16 and 17 are slightly irregular owing to the use of points calculated for the half-sections. In Figs. 18 to 24 inclusive, only points for whole sections were used for the peaks.

TABLE III.

Values of h.

$m_s-.5$	h_a	$\sum^{m_s-.5} h_a$	$\sum^{m_s-.5} h_a$	$\sum^{m_s-.5} h_a$	$\sum^{m_s-.5} h_a$	$\sum^{m_s-.5} h_a$	$\sum^{m_s-.5} h_a$	$\sum^{m_s-.5} h_a$	$\sum^{m_s-.5} h_a$	$\sum^{m_s-.5} h_a$	$\sum^{m_s-.5} h_a$	$\sum^{m_s-.5} h_a$
		.5										
0.5	.716	.716										
			1.5									
1.5	.171	.886	.171									
				2.5								
2.5	.0512	.937	.222	.0512								
					3.5							
3.5	.0207	.958	.243	.072	.021							
						4.5						
4.5	.0102	.968	.253	.082	.031	.010						
							5.5					
5.5	.0057	.974	.259	.088	.037	.016	.0057					
								6.5				
6.5	.0035	.978	.262	.091	.040	.019	.0092	.0035				
									7.5			
7.5	.0023	.980	.264	.094	.042	.022	.0115	.0058	.0023			
										8.5		
8.5	.0016	.982	.266	.095	.044	.023	.0131	.0074	.0039	.0016		
											9.5	
9.5	.0011	.983	.267	.096	.045	.025	.014	.0086	.0051	.0027	.0011	
												10.5
10.5	.00085	.984	.268	.097	.046	.025	.015	.0094	.0059	.0036	.0020	.00085
11.5	.00065	.984	.269	.098	.047	.026	.016	.0101	.0066	.0042	.0026	.00150

TABLE IV

m_s	h_a	m_s	h_a
0.	1.000	1.1	0.304
0.1	0.985	1.2	0.262
0.2	0.943	1.3	0.227
0.3	0.879	1.4	0.196
0.4	0.800	1.5	0.171
0.5	0.716	1.6	0.149
0.6	0.631	1.7	0.130
0.7	0.550	1.8	0.114
0.8	0.476	1.9	0.101
0.9	0.411	2.0	0.089
1.0	0.354		

The coefficient of m.m.f. for the plunger circuit is f_p. Its value is

$$f_p = \int_z^{l_p} h \, d \, l_p \tag{32}$$

wherein l_p is any distance along the horizontal axis of the solenoid (abscissas in the figures). In this paper it represents the point at which the inserted end of the plunger rests.

The l_p curves were obtained directly from the h curves by integrating with a planimeter from the extreme left-hand point of each curve.

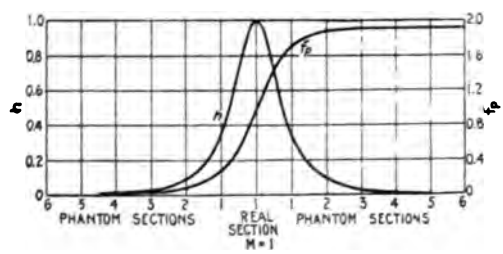


FIG. 14

In each of the above figures, the maximum value of f_p approaches the limit

$$f_{max} = 2\,m \tag{33}$$

wherein m is the number of sections in the solenoid. The total m.m.f. is, of course, equally divided on each side of the center of the solenoid.

A convenient method of analyzing the action of a solenoid and plunger is to think of the plunger as having been inserted

(from the left in the figures) for a given distance, say to the middle of the solenoid, and then conceiving the m.m.f. as consisting of two components, one of which produces the magnetizing force to magnetize the plunger while the other component produces the

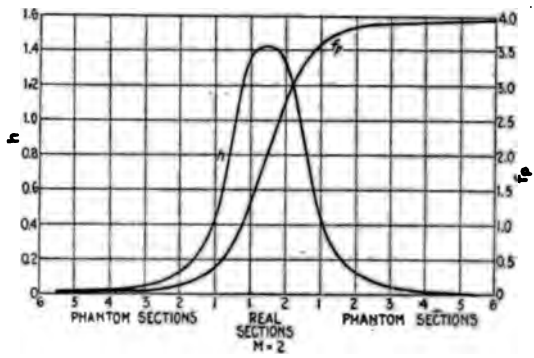


FIG. 15

magnetizing force to coact with the flux in the plunger and thus cause attraction.

The value f_p bears the same relation to the m.m.f., F_p, that h bears to the magnetizing force. Therefore,

$$F_p = 0.2\,\pi\, i\, n\, f_p \tag{34}$$

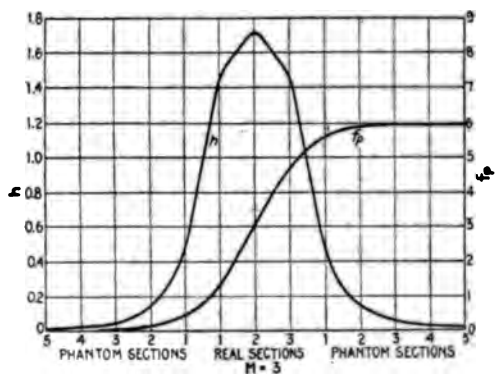


FIG. 16

Hence, at the middle of any solenoid, the m.m.f. available to magnetize the plunger is but one-half of the total, while, at other points along the horizontal axis of the solenoid, the values of f_p are to be read from the curves.

The magnetic circuit of the plunger may be considered as consisting of that portion of the plunger which is inserted into the solenoid and the surrounding air or non-magnetic region between the inserted end of the plunger and the end of the solenoid at

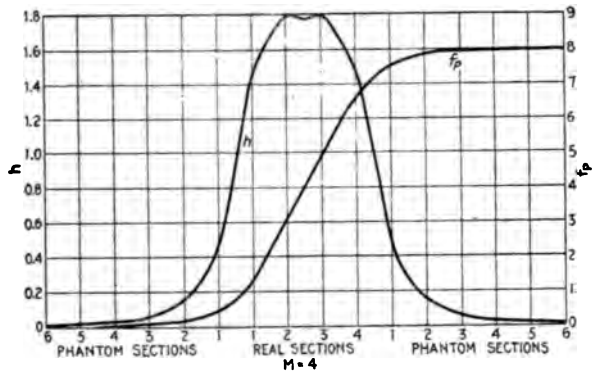


FIG. 17

which the plunger enters. Actually, the flux enters or leaves the protruding plunger over the entire area of that part of the plunger. Practically, it is convenient to assume that it enters the plunger between a point, equal to one-half of one section-length from the

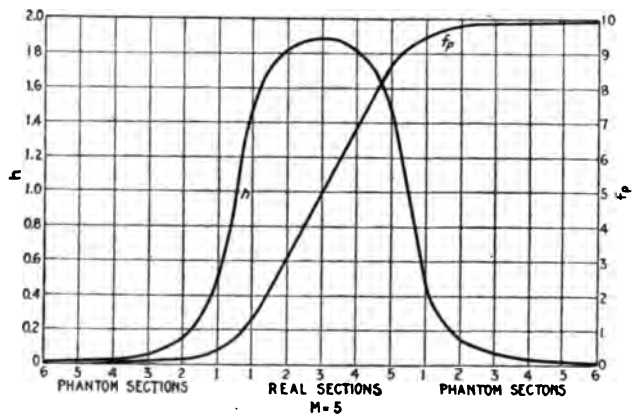


FIG. 18

end of the solenoid at which the plunger enters, and the middle of the plunger. This makes it possible to consider the point l_p as being at the center of the section of the same number as the point. Thus, at the center of the third section from, say, the left-hand end of the solenoid, $l_p = 3$.

As the plunger passes into the solenoid, the iron flux ϕ_i, which is equal to $S\,(B - H)$, increases, and the pull, for a constant value of H, will increase directly with ϕ_i until saturation is attained. Thereafter, the pull

$$P = \frac{\phi_i\, i\, n\, h}{1962\, L} \times 10^{-4} \tag{12}$$

will remain constant.

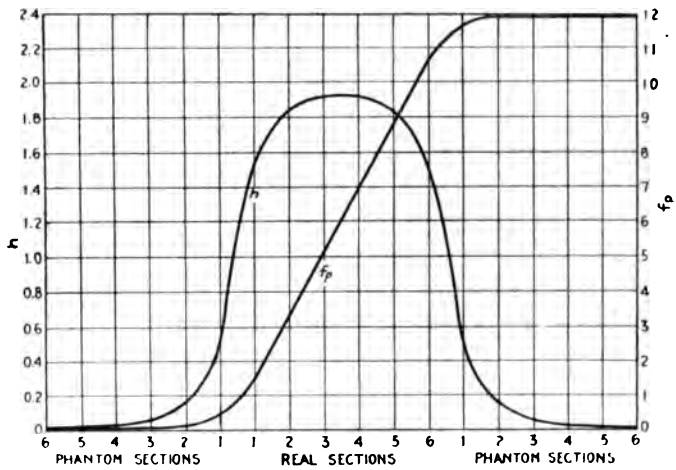


FIG. 19

After the plunger is saturated, the pull will vary directly with $H = i\, n\, h$. That is, the pull will be

$$P = \frac{H\, S\,(B - H)}{1962\, L} \times 10^{-4} \tag{35}$$

The plunger or iron flux ϕ_i may be called the average effective flux.

One portion of the plunger m.m.f. is required to overcome the reluctance of the plunger, and the other portion forces the flux through the air from the inserted end of the plunger to the end of the solenoid at which the plunger enters.

This leads to the problem of ascertaining the reluctance of the air-return circuit. The mean length of this portion of the plunger circuit is somewhere between 0 and ∞ while the cross-section is

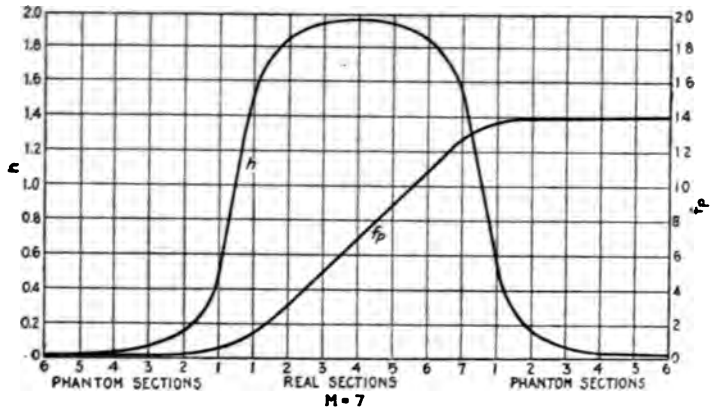


FIG 20

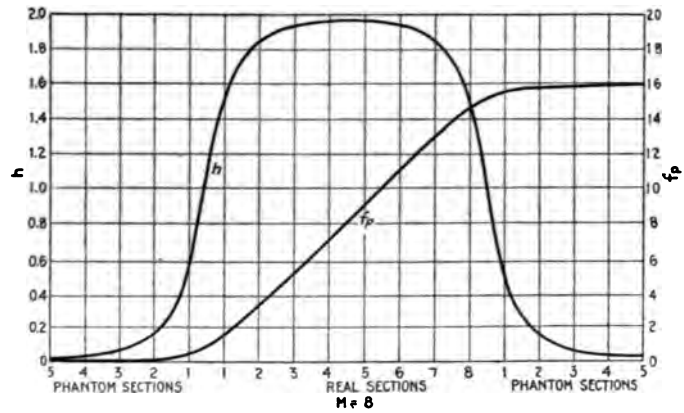


FIG. 21

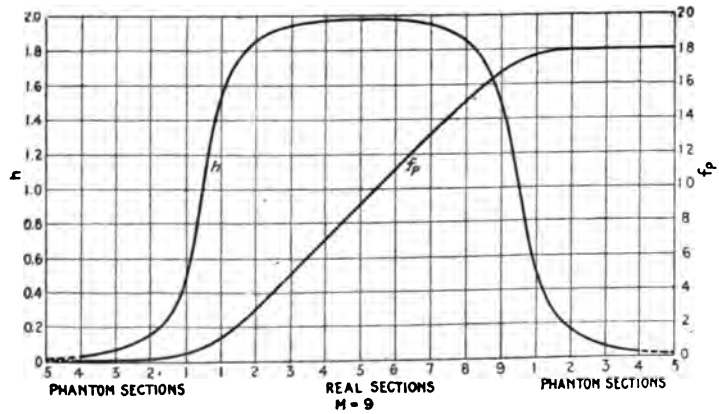


FIG. 22

infinite. It is difficult to obtain accurate experimental data owing to the fact that the plunger is not uniformly magnetized, but may be saturated at or near the middle of that portion within the solenoid, with lessening degrees of magnetization on either side of this point.

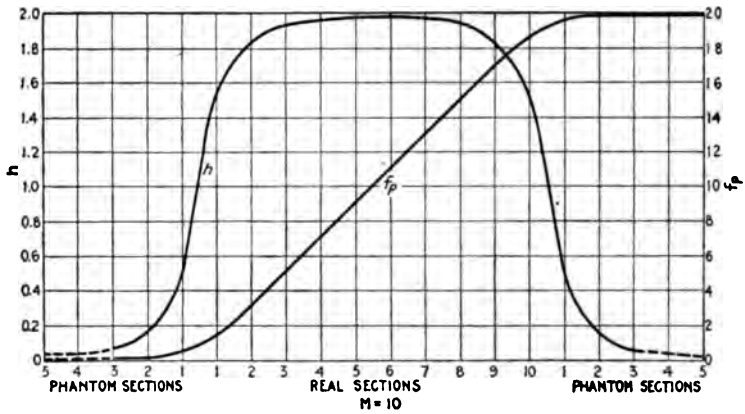


FIG. 23

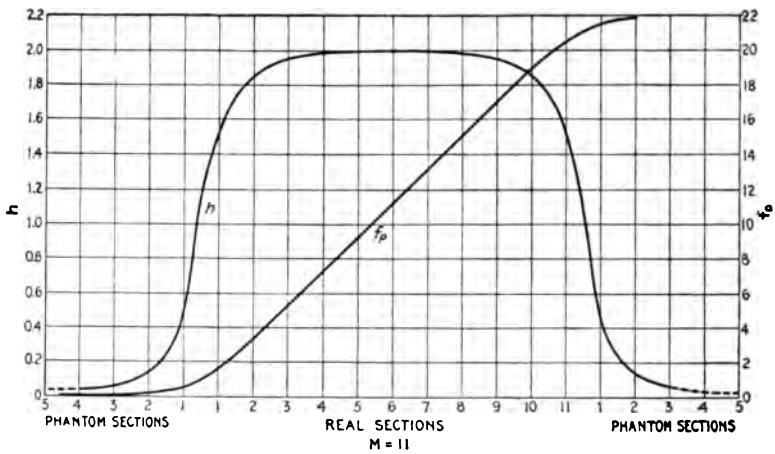


FIG. 24

The average reluctance of the air portion of the plunger circuit is the difference between the total average reluctance of the plunger circuit and the reluctance of the plunger.

$$R_a = \frac{F_p}{\phi_i} - \frac{l_p r}{S(\mu_i - 1)} \tag{36}$$

wherein ϕ_i is the total flux in the plunger circuit, l_p is the length of the plunger, in section-lengths, inserted into the solenoid, S the cross-sectional area of the plunger in sq. cm., and μ_i the average permeability of the plunger.

In Fig. 25 are shown the test characteristics of an eleven-section solenoid 30.5 cm. long and of 2.76 cm. average radius. The plunger was of Swedish iron 6.45 sq. cm. in cross-section and one meter in length. The two dotted curves represent the values of h plotted to such scales as to be readily compared with the corresponding pulls.

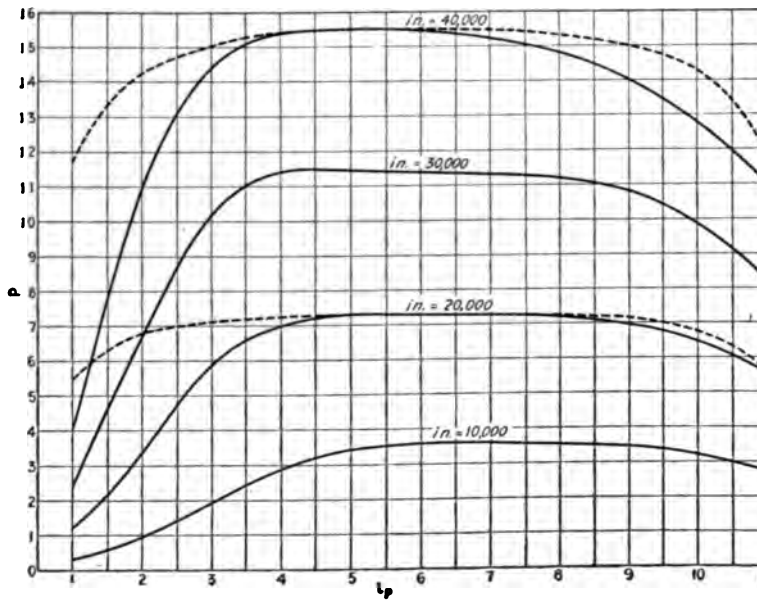


FIG. 25

The average plunger flux is calculated from these data by rearranging (**12**). Then

$$\phi_i = 1962 \frac{P\,L}{i\,n\,h} \times 10^4 \tag{37}$$

Fig. 26 shows the calculated values of $\frac{\phi_i}{S}$ plotted against points representing the centers of the sections of the solenoid. The calculated values of $\frac{F_p}{\phi_i}$ are also plotted in Fig. 26. The average

air reluctance can only be calculated from the test data below saturation. The slopes of the curves indicate that the total reluctance below saturation is less than 0.1 oersted.

The calculated flux-densities are, necessarily, only averages. Owing to the relatively low calculated reluctances with the lower m.m.fs., it is evident that the inserted plunger may be highly saturated at and near the middle of that part inserted. As the m.m.f. is increased, a greater portion of the inserted plunger be-

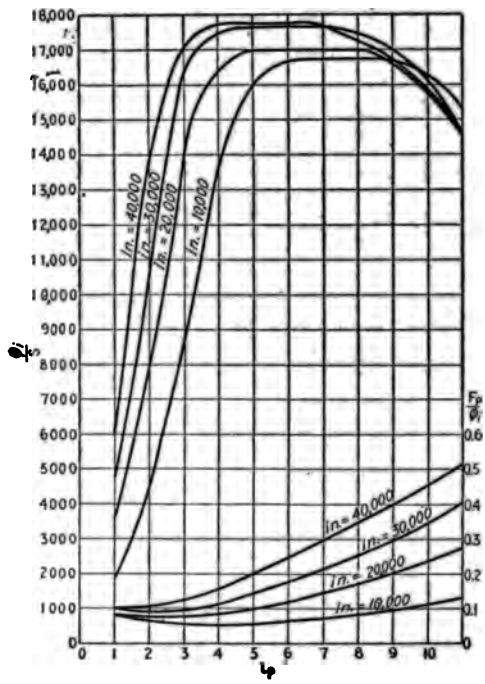


FIG. 26

comes highly saturated; but the entire inserted portion will not be uniformly magnetized, owing to the leakage from all parts of its surface.

Under these conditions, the average reluctance of the plunger might be in excess of that of the air-portion of the magnetic circuit. In the case of the eleven-section solenoid, the length of the coil was 30.5 cm. The cross-sectional area of the plunger was 6.45 sq. cm. The reluctance of that portion of the plunger inserted into the entire length of the solenoid would, therefore,

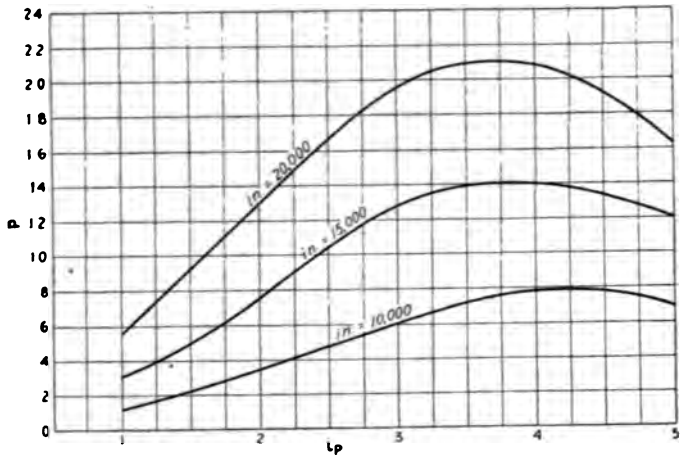

24
22
20
18
16
14
12
10
8
6
4
2
0
P
1
2
3
4
5
l_p
$in = 20,000$
$in = 15,000$
$in = 10,000$

FIG. 27

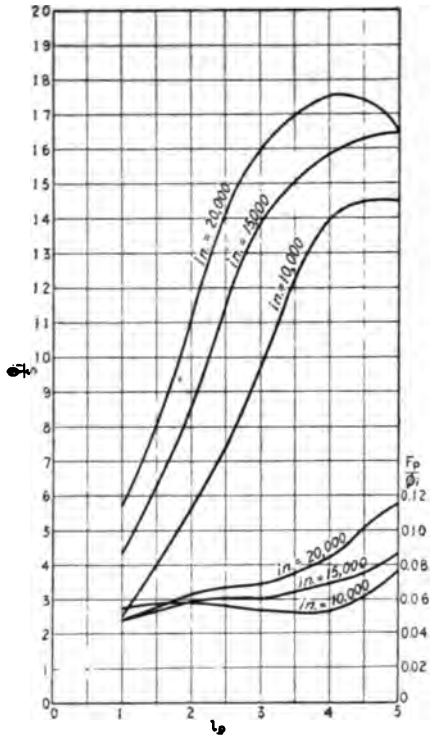

20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
ϕ_{th}
F_p
ϕ_i
0.12
0.10
0.08
0.06
0.04
0.02
0
1
2
3
4
5
l_p
$in = 20,000$
$in = 15,000$
$in = 10,000$
$in = 20,000$
$in = 15,000$
$in = 10,000$

FIG. 28

be 4.73 oersteds with unit permeability. With an average permeability of 20, the average reluctance would be 0.237 oersted, exclusive of that of the air-return circuit.

Fig. 27 shows the results of a test of a five-section solenoid of 3.5 cm. average radius. The plunger was of cold-rolled steel 11.4 sq. cm. in cross-section and approximately 25 cm. long. The length of the solenoid was 17.8 cm. Fig. 28 shows the calculated flux-densities and reluctances. This figure shows lower total reluctances owing to the greater cross-section of the plunger.

The reluctance of the non-magnetic region surrounding a plunger must be nearly constant throughout the entire travel of the plunger because the leakage area of the plunger increases directly with the distance that the plunger is inserted into the solenoid. This

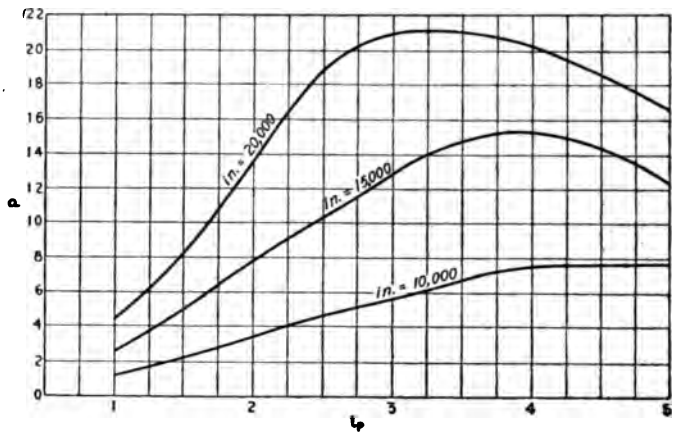


FIG. 29

leakage surface is directly proportional to the diameter of the plunger. The diameters of the plungers used in the tests of the eleven-section and five-section solenoids were 2.8 cm. and 3.8 cm. respectively. Hence, the ratio of the reluctance of the surrounding air-spaces should be as 1 to 0.74. Taking the air reluctance of the five-section solenoid as 0.06 oersted, that for the eleven section solenoid should be 0.081 oersted. The air reluctances are probably lower than assumed.

In Fig. 29 are shown the calculated characteristics of the five-section solenoid, the assumptions being that the total reluctance of the plunger circuit has a constant value of 0.06 oersted and that the limit of the average structural flux density is 17,000. The calculated flux densities are shown in Fig. 30.

Fig. 29 compares favorably with Fig. 27, excepting that the maximum pull due to 15,000 ampere-turns is in excess of the test data, and the maximum pull due to 20,000 ampere-turns occurs at a point somewhat to the left of the point observed in the test. This is largely due to the straight-line magnetization curve assumed as in Fig. 30. It is to be observed that the pulls at other points on the curves compare favorably with the test data, proving that the reluctance of the air-portion of the magnetic circuit must be low.

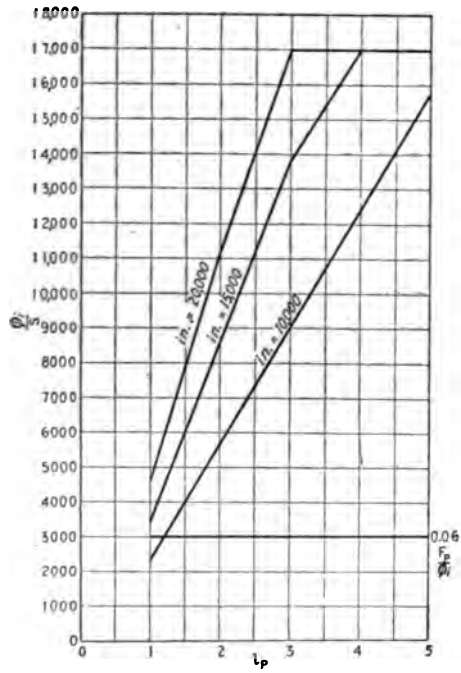


FIG. 30

Fig. 31 shows the calculated characteristics of the eleven-section solenoid. The assumptions are the same as those used in the calculation of the five-section solenoid, excepting that the assumed constant reluctance is 0.081 oersted. The calculated flux-densities are shown in Fig. 32.

The remarks regarding Fig. 29 apply to Fig. 31 also. The pulls do not become at a maximum at the same points as in the test curves and there is some variation in these pulls. The former is to be expected with a straight-line magnetization curve from

zero to saturation. The reluctances of the plungers vary with different degrees of magnetization and the saturation points of the plungers, as well as constant reluctances, are assumed. The test data indicate that the total reluctance varies with the m.m.f.

The effects of the apparent reaction which takes place as the magnetic center of the plunger approaches the magnetic center of the solenoid, are evident in Fig. 28. As is well known, all relative movement ceases when these two points coincide. In these tests, the plungers were considerably longer than the solenoids.

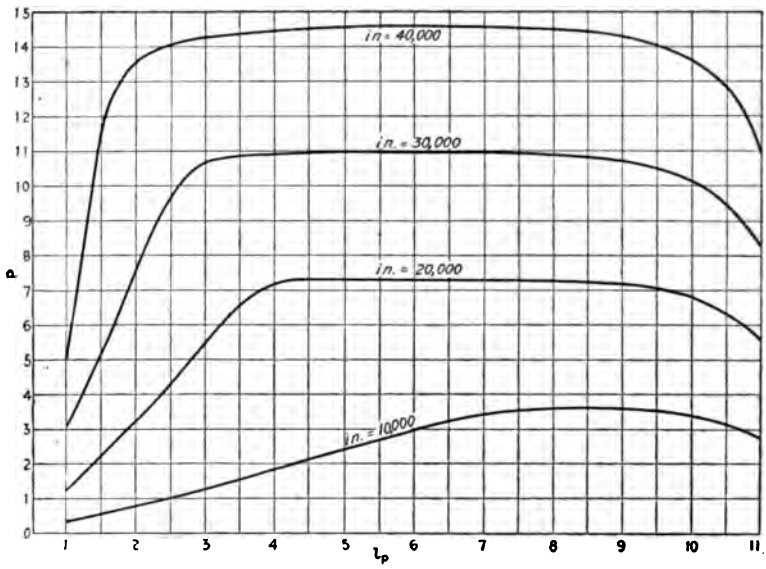


FIG. 31

Figs. 27 and 29 illustrate the action of a solenoid-and-plunger very nicely. When the flux density in the plunger is low, the maximum pull may occur at a point near the end of the solenoid opposite to that at which the plunger enters, whereas, with high flux-densities, the maximum pull may occur when the inserted end of the plunger is at the middle of the solenoid. The pull cannot be at a maximum at points between the middle of the solenoid and the end at which the plunger enters, although it may be nearly uniform for equal distances on both sides of the middle, in cases of long solenoids. In cases of very short solenoids

the maximum pull may occur at points outside of the solenoid at the end opposite to that at which the plunger enters.

Owing to the low reluctances of the plunger circuits of this type of electromagnet, the equation

$$P_d = \frac{\phi_i^2}{8\,\pi\,S} \tag{38}$$

cannot be applied to predetermine the pull due to plunger electromagnets, excepting for zero air gap. Equation (**38**) is not general,

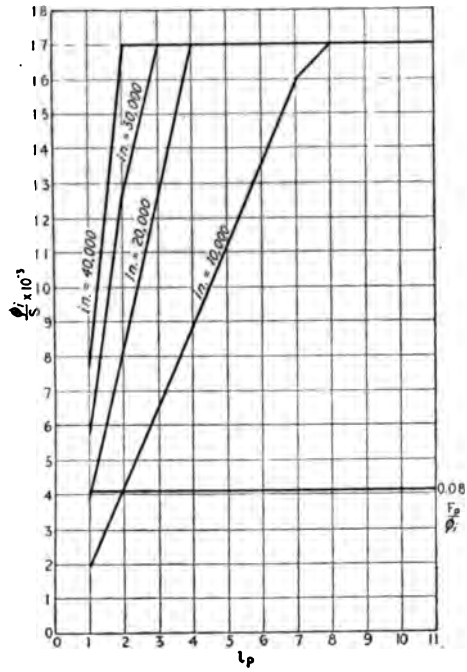


FIG. 32

but is for the attraction proportional to $(B - H)^2$ between the plunger and the stop only. On account of the leakage from the end of the inserted plunger back through the air and frame to the end of the solenoid at which the plunger enters, when there is an air gap, the flux densities in the plunger may be much greater than assumed, when the assumption is that nearly all of the flux passes through the air gap.

The magnetic circuit of an iron-clad stopped solenoid, or plunger electromagnet, consists of more than one path. The m.m.f.

forces flux through the air gap but it also forces another flux from the end of the plunger through the air and frame and back to the opposite end of the plunger. This latter flux produces a relatively strong pull whether any flux passes through the air gap, between the plunger and the stop, or not. There are, therefore, two separate and distinct actions to be considered, viz: the pull due to the flux density, $B - H$, in the air gap and the pull due to the flux in the plunger coacting with the magnetizing force due to the ampere turns in the solenoid.

One of the assumptions upon which Maxwell's fundamental equation is based, is that there is no air gap whatsoever between the abutting ends of the hypothetically-separated core of the bar electromagnet. Hence Maxwell's equation was not intended for tractive electromagnets. The conditions imposed by Maxwell clearly indicate that no work can be done by such an electromagnet. It is further assumed that the magnetic circuit is identical with that of a bar electromagnet; that is, that the flux is equally distributed on each side of the middle of the hypothetical zero air gap and that there is no leakage whatsoever from the abutting ends of the half-cores back to the opposite end of the same half-core.

Therefore, the conditions imposed for the application of Maxwell's fundamental equation (**38**) are entirely different from those met with in tractive electromagnets; particularly that type known as the plunger electromagnet.

In the application of equation (**38**) it is customary to add together the reluctances of the air gap, plunger, stop, frame and the non-magnetic joint between the plunger and the frame where the former passes through the latter. The total m.m.f. is then divided by the total reluctance and the resulting flux is assumed to be the total flux in the magnetic circuit, and to be the same in the air gap as in the plunger and stop. Allowance for leakage is seldom made because the pulls, with moderately long air gaps, are usually found to be in excess of those calculated. The total flux divided by the cross-sectional area of the plunger is called the magnetic induction B in the plunger and this value is also usually assumed for the flux-density in the air gap. When the reluctance of the air gap is equal to the sum of the reluctances of the rest of this single magnetic circuit, the maximum amount of work is assumed to be obtainable, when work is defined as initial pull $\times$ length of air gap.

The total pull, by Maxwell's equation (**3**), as modified by

neglecting the last term of the right-hand member (which is not available in a solid coil), is

$$P_s = 2\pi I^2 + I H \tag{39}$$

in dynes per sq. cm.

$$P_t = 2\pi I^2 \tag{40}$$

is the structural pull, in dynes per sq. cm., between the abutting ends only of the half-cores of the bar electromagnet.

Now when an air gap is introduced between the plunger and the stop, the intensity of magnetization in the iron does not decrease with the flux density (less H) in the air gap on account of the leakage from the inner end of the plunger, through the air or ether, back to the end at which the plunger enters the coil.

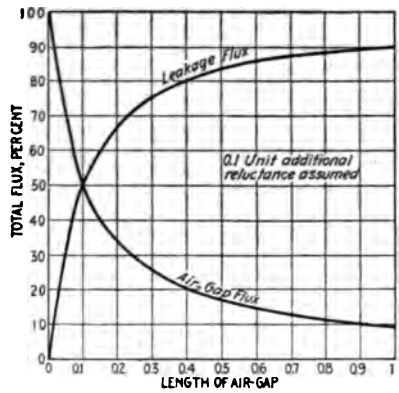


FIG. 33—RELATIVE VALUES OF FLUX

This leakage tends to sustain the intensity of magnetization in the plunger and to produce the "solenoid pull" when the flux density(less H) in the air gap is exceedingly low, or when there is no air gap (in the usual sense) as when only the plunger is inserted into the coil and there is no other magnetic material near.

Generally speaking*, the leakage pull is a maximum when the length of the air gap in a plunger electromagnet is maximum, but when the length of the air gap is reduced to zero, there can be no leakage (as mentioned above) whatsoever, and the law of the pull required to separate the plunger from the stop is then expressed by equation (39). On the other hand, the air gap

*See "Alternating-Current Electromagnets," *Electrical World*, Vol. 63, No. 5, p. 260 (1914).

flux will vary inversely with the length of the air gap so that the general conditions, so far as the air gap and leakage fluxes are concerned, are graphically represented in Fig. 33.

It will now be seen that Maxwell's law is true for a closed air gap, under the ideal conditions previously mentioned, but that it does not hold for tractive electromagnets unless modified to allow for the extra pull due to leakage. Therefore, the equation for the total pull due to a plunger electromagnet with an air gap and fixed stop may be constructed as follows: From (**7**), $\frac{\phi_i}{S} = 4\,\pi\,I$, wherein ϕ_i is the total structural flux in the iron. Let ϕ_g represent the flux in the air gap less that due to the magnetizing force, and allow P_g to represent the pull in dynes per sq. cm. in the air gap due to ϕ_g. Then

$$P_g = \frac{\phi_g^2}{8\,\pi\,S^2} \tag{41}$$

Expressed in dynes,

$$P_g = \frac{\phi_g^2}{8\,\pi\,S} \tag{42}$$

The pull in kilograms, under the above conditions, is

$$P_G = \frac{\phi_g^2}{8\,\pi \times 981{,}000\,S} = \frac{\phi_g^2}{247\,S} \times 10^{-4} \tag{43}$$

Adding equations (**43**) and (**12**), the total pull, in kilograms, for a plunger electromagnet, with or without an iron frame, or a stop, is

$$P = \left(\frac{\phi_g^2}{247\,S} + \frac{\phi_i\,i\,n\,h}{1962\,L}\right) \times 10^{-4} \tag{44}$$

which is the general pull equation for tractive electromagnets of the plunger type.

The flux in the stop also coacts with the magnetizing force in the coil which tends to produce motion, but the stop and coil are usually fixed in position so that no relative motion results. The leakage, from the inserted end of the stop back through the air and frame to the place where it is attached to the frame, tends to cause a greater total flux to pass through the stop than is usually calculated. This causes the reluctance of the stop to be greater than calculated, on the assumption that the flux in the plunger and stop is the same as that in the air-gap.

In Fig. 34* are shown the test characteristics of the eleven-section solenoid, 30.5 cm. long, surrounded by a massive wrought iron frame. The stop was of the same material and of the same diameter as the plunger and was inserted 7.6 cm. into the coil. All curves are due to 10,000 ampere-turns. The curve P_t is due to the plunger electromagnet complete; that marked P_s is due to the solenoid-and-plunger only, and the curve marked P_g is the difference between the above curves. Hence

$$P_g = P_t - P_s \tag{45}$$

represents the pull due to the flux in the air-gap. l_g is the length of the air gap in centimeters.

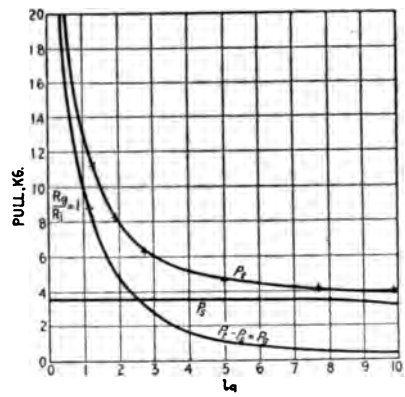


FIG. 34—PULL CHARACTERISTICS OF THE ELECTROMAGNET TESTED

The points marked on the curve P_t are the actual test data for the total pull. The rest of the curve P_t was calculated in the manner described below.

In what follows, the reluctance R_g of the working air gap is assumed to vary directly with the distance between the plunger and the stop. A trial calculation from the test data indicated a nearly-constant reluctance, external to the working air-gap, of 0.17 oersteds. Taking this as a basis, the curve P_t, which agrees closely with the test data, was obtained by adding the calculated air-gap pulls to those due to the solenoid-and-plunger only.

*Part of the following is abstracted from *Electrical World*, Vol. 59, No. 25, p. 1388 (1912).

The m.m.f. for the air gap is

$$F_g = \frac{R_g F_t}{R_g + R_i} \tag{46}$$

wherein F_t is the total m.m.f. (12,570 gilberts), R_g the reluctance of the working air gap, and R_i the sum of the reluctances of the plunger, stop, frame, and non-magnetic joint between the plunger and the frame. Then the flux in the air gap is

$$\phi_g = \frac{F_g}{R_g} \tag{47}$$

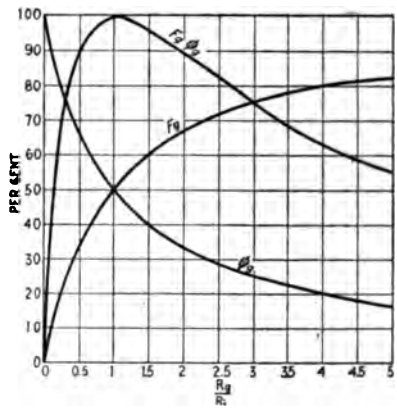


FIG. 35—FORCE, THEORETICAL FLUX AND ENERGY CURVES FOR AIR GAP

The pull due to the flux in the air gap was calculated by equation (**43**).

It has been theoretically proved that the maximum amount of work (initial pull × length of air gap) may be obtained from a plunger electromagnet when the reluctance of the working air-gap is equal to that of the rest of the magnetic circuit.* This is similar to the rule for the maximum wattage which may be obtained in an electrical apparatus connected in series with a line. The general principle is illustrated in Fig. 35, wherein R_i is assumed to be constant. The product of m.m.f. and flux, in the air gap, becomes a maximum when $R_g = R_i$. $F_g \phi_g$ is, in a way, analogous to the e.m.f. multiplied by the current strength.

*E. R. Carichoff, *Electrical World*, Vol. XXIII, pp. 113 and 212 (1894).

The point marked $\frac{R_g}{R_i} = 1$, on the curve P_g in Fig. 34, is where the reluctance of the air gap is 0.17 oersted, which is the same as the calculated reluctance for the rest of the magnetic circuit.

Fig. 36 shows the calculated air gap characteristics of the test

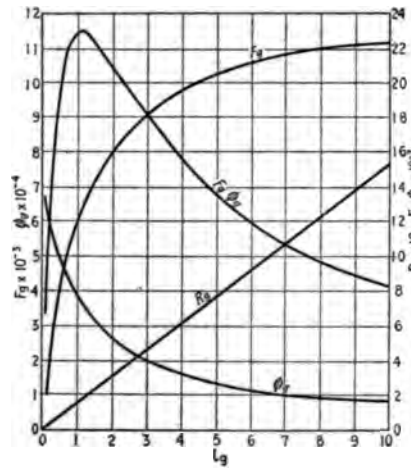


FIG. 36—CALCULATED AIR GAP CHARACTERISTICS OF TEST ELECTROMAGNET

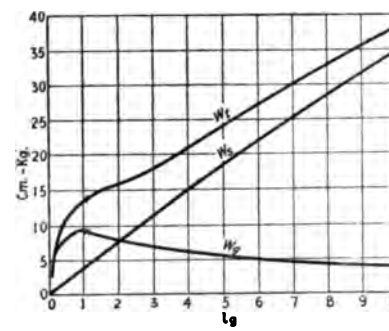


FIG. 37—WORK CURVES OF TEST ELECTROMAGNET

electromagnet. The calculated values of $F_g\ \phi_g$ become at a maximum when the air gap is 1.1 cm. in length, which is the point where $R_g = R_i$.

The centimeter-kilograms of work, for varying lengths of air gap, obtained with the test electromagnet, are shown in Fig. 37. W_t is the pull $\times$ distance which was actually obtained with the

complete plunger electromagnet, while W_s is the actual pull $\times$ distance obtained with the coil-and-plunger only. The curve marked W_g represents the difference between curves W_t and W_s.

Therefore, the maximum amount of work as defined above which may be obtained with a plunger electromagnet, with a given m.m.f., is not directly dependent upon the equality of the reluctance of the air gap and the sum of the reluctances of the rest of the magnetic circuit.

The amount of work which may be obtained with a plunger electromagnet becomes at a maximum when the range or distance of travel of the plunger times the sum of the pulls, due to the flux in the air gap and to the flux in the plunger coacting with the magnetizing force, become at a maximum.

The latter rule is general and is applicable to all forms of plunger electromagnets, with or without stops or frames, whether designed for alternating or direct currents. When the air gap reluctance and total m.m.f. are of low value, the pull due to the "solenoid effect" may be negligible, but this pull increases with the m.m.f. and is very marked when the air gap reluctance is relatively high.

The designs of alternating- and direct-current plunger electromagnets differ, generally, only in their windings and ferric parts; the law governing the mean effective pull applies to both.

DISCUSSION ON "SOLENOIDS" (UNDERHILL), WASHINGTON, D. C., APRIL 24, 1914.

Charles W. Burrows: I would like to call attention to a few points in which I am not in complete agreement with the author.

In the first place, Tables I to IV used in the calculation of the magnetic field are given* out to the sixth place of decimals. As the assumptions made in the computations did not seem to warrant such precision I recalculated some of the results by a more precise formula, as follows:

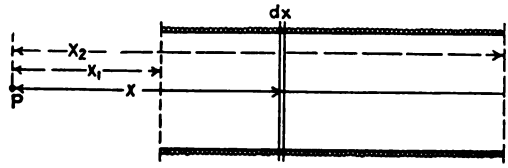


FIG. 1

The magnetic field at any point on the axis of a solenoid is given by the equation

$$H = 0.2\,\pi\,n\,I \int \frac{r^2}{(r^2 + x^2)^{3/2}\,dx} \qquad (1)$$

where

H = magnetizing force of solenoid
n = number of turns per cm.
x = axial distance of element of coil
r = radius of coil
I = current in amperes in coil.

The integration of equation (1) gives

$$H = 0.2\,\pi\,n\,I \left[\frac{x}{\sqrt{r^2 + x^2}}\right]_{x_1}^{x_2}$$

$$= 0.2\,\pi\,n\,I \left[\frac{x_2}{\sqrt{r^2+x_2^2}} - \frac{x_1}{\sqrt{r^2+x_1^2}}\right] \qquad (2)$$

where x_1 and x_2 (Fig. 1) are the distances from the point where H is measured to the two bounding planes of the solenoid.

If we measure x in terms of r and let

$$\alpha_1 = \frac{x_1}{r} \text{ and } \alpha_2 = \frac{x_2}{r}, \text{ then}$$

$$H = 0.2\,\pi\,n\,I \left(\frac{\alpha_2}{\sqrt{1 + \alpha_2^2}} - \frac{\alpha_1}{\sqrt{1 + \alpha_1^2}}\right) \qquad (3)$$

*In the paper as originally printed.

The quantity enclosed in parentheses is a more exact expression for what is called h in the paper.

$$h = \left(\frac{\alpha_2}{\sqrt{1+\alpha_2^2}} - \frac{\alpha_1}{\sqrt{1+\alpha_1^2}}\right) \tag{4}$$

At the center of a coil one radius long

$$\alpha_2 = +\frac{1}{2}$$

$$\alpha_1 = -\frac{1}{2}$$

$$h = \left(\frac{\frac{1}{2}}{\sqrt{1+\left(\frac{1}{2}\right)^2}} - \frac{-\frac{1}{2}}{\sqrt{1+\left(\frac{1}{2}\right)^2}}\right)$$

$$= \frac{2}{\sqrt{5}} = 0.894$$

and not unity as given in the table.

For an adjoining similar solenoid

$$\alpha_1 = \frac{1}{2}$$

$$\alpha_2 = \frac{3}{2}$$

$$h = \left(\frac{\frac{3}{2}}{\sqrt{1+\left(\frac{3}{2}\right)^2}} - \frac{\frac{1}{2}}{\sqrt{1+\left(\frac{1}{2}\right)^2}}\right)$$

$$= \frac{3}{\sqrt{13}} - \frac{1}{\sqrt{5}} = 0.385$$

and not 0.363560 as given in the table.

Consequently in Table I, page 487, the column headed h_a should be corrected as follows:

m_b	h_a as given	h_a as corrected
1	0.353560	0.385
2	0.089443	0.096
etc.	etc.	etc.

These errors are transferred to Table II on page 488, where column 1 should be corrected as follows:

Column 1 as given	Column 1 corrected
1.0000000	0.894
1.353560	1.279
1.443003	1.376

The most accurate figure in this table is in column 6, where the number 1.992872 should be replaced by the true value 1.968.

All these errors are due to the assumption that the formula for the field at the center of a single turn holds for a layer whose length is equal to the radius. The errors may be eliminated or reduced by taking as elements shorter lengths, as Mr. Underhill has done in his book on "Solenoids," or individual turns, as Thompson has done.

Even though suitable accuracy is obtained in this way, I do not believe the method is valuable, since the desired results can be obtained more simply otherwise.

Instead of calculating the force due to each individual element of a solenoid we may approach the matter from a somewhat different point of view.

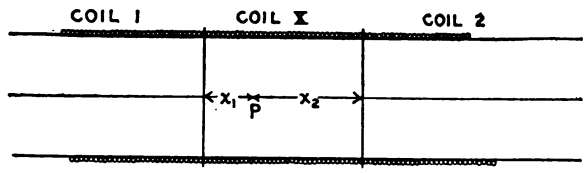


FIG. 2

Any finite solenoid as coil X (Fig. 2) may be considered as having been made from an infinite solenoid by removing the two infinite portions represented by coil 1 and coil 2. The magnetic field within the solenoid X at a point P on the axis, distant from its bounding planes by x_1 and x_2, respectively, is then equal to the field due to the original infinite solenoid minus the fields produced at the point P by the coils 1 and 2. The field due to coil 2 is given from equation (3) by making $\alpha_2 = \infty$.

Then

$$H_2 = 0.2\,\pi\,n\,I\left(1 - \frac{\alpha_1}{\sqrt{1+\alpha_1^2}}\right) = 0.2\,\pi\,n\,I\,h_2$$

Similarly, the field due to coil 1 is

$$H_1 = 0.2\,\pi\,n\,I\left(1 - \frac{\alpha_2}{\sqrt{1+\alpha_2^2}}\right) = 0.2\,\pi\,n\,I\,h_1$$

where α_1 and α_2 are the distances, in terms of the radius, of the point P beyond the free ends of the coils 2 and 1 respectively.

For the original infinite solenoid

$$H = 0.2\,\pi\,n\,I \times 2$$

so that for the finite coil (X),

$$H = 0.2\,\pi\,n\,I\,(2 - h_1 - h_2)$$

h_1 and h_2 may be called the end corrections and are tabulated in Table I and shown in Fig. 3.

TABLE I

Showing the end effects of a solenoid, where h_1 and h_2 refer to the corrections for the two ends of the solenoid.

0.0	1.0000
0.1	0.9005
0.2	0.8039
0.3	0.7126
0.4	0.6286
0.5	0.5527
0.6	0.4855
0.7	0.4266
0.8	0.3755
0.9	0.3310
1.0	0.2928
1.5	0.1681
2.	0.1056
3.	0.0511
4.	0.0300
5.	0.0195
6.	0.0136
7.	0.0102
8.	0.0080
9.	0.0064
10.	0.0050

The data of this table are plotted in Fig. 3.

To use this table let us calculate the field at a point on the axis of a coil ten radii long at a point two radii distant from one end. From the table,

$$\begin{aligned} h_2 &= 0.1056 \\ h_3 &= \underline{0.0080} \\ h_2 + h_3 &= 0.1136 \\ 2 - 0.1136 &= 1.8864 \end{aligned}$$

so that

$$H = 0.2\,\pi\,n\,I \times 1.8864$$

On page 491 we find "* * * * * conceiving the m.m.f. as consisting of two components, one of which produces the magnetizing force to magnetize the plunger while the other component produces the magnetizing force to coact with the flux in the plunger and thus cause attraction."

Instead of considering that the plunger is fully magnetized and the m.m.f. is divided into two portions, one of which magnetizes but does not attract and the other of which attracts but does not magnetize, I look at the matter somewhat differently.

I consider that the entire m.m.f. is used to magnetize the plunger and that the entire m.m.f. is also used to react on the magnetized plunger. To be sure, the magnetic induction produced is not the greatest possible for the given m.m.f. because of the relative positions of the solenoid and plunger, and also because of the self-demagnetizing influence, which has been neglected entirely.

The formula (**35**) on page 493 is not strictly correct. This is evident when we consider the special case of the bar located symmetrically within the solenoid. According to the formula the pull in this position should be a maximum. However, we know from experimental evidence that the pull is zero. It would be better to say that the pull is proportional to the product of the field strength and the leakage from the bar. This is equivalent

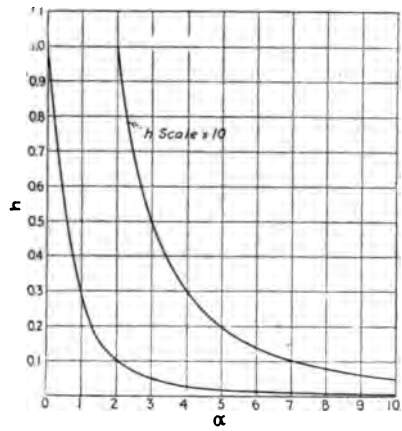


FIG. 3—CURVE SHOWING THE VARIATION OF α AND h.

to saying that the pull is due to the reaction between the magnetic field and the free poles.

Fig. 26 presents some anomalies. When the plunger is inserted almost to the far end of the solenoid the figure shows that 10,000 ampere-turns give rise to a greater induction than 40,000. As it is obviously impossible that the larger m.m.f. should give rise to the smaller induction, the premises on which these data were calculated must be in error. Equation (**37**), page 496, used in the calculations of the data for these curves, is open to the same objections as those brought against equation (**35**). The error due to assuming that this equation holds, may be enough to account for the discrepancy.

E. R. Carichoff: In his reference to my paper published in 1894, what Mr. Underhill mentions is only a corollary to my proposition, and this corollary is true only when μ is supposed to be constant. My proposition deals with certain definite assumptions, one of which is only approximately true—viz., the assumption of no leakage.

I will give here substantially the discussion—Having given a magnet of definite length and cross-section, an air gap of given length, and any constant magnetomotive force, to find the polar area that will give a maximum force.

In the formulas, A, L, B and H represent respectively the area, length, induction and magnetic force for the air gap, and a, l, b and h the same quantities for the iron, the flux in the air gap and in the iron being assumed to be the same.

$$P \propto A B^2 \propto A H^2 \tag{1}$$

$$\frac{dP}{dA} = 2 A H \frac{dH}{dA} + H^2 = 0$$

for maximum force, or

$$2 A \frac{dH}{dA} + H = 0 \tag{2}$$

The condition of constant m.m.f. is

$$HL + hl = \text{constant}. \tag{3}$$

The condition of no leakage is

$$AH = a b \tag{4}$$

By differentiating (3) and (4) with respect to A and substituting in (2) we have the relation

$$\frac{a\, db}{l\, dh} = \frac{A}{L} \tag{5}$$

This means that the tangent to the curve representing the permeance of the iron equals the permeance of the air gap; and further, if μ is constant it means reluctance of iron = reluctance of air gap.

Again, if the polar area is constant and the length of the air-gap is made a variable, the other conditions remaining as before, and the problem is to find the length of air gap that will make the product of force times length of air gap a maximum, we have

$$W \propto A B^2 L = A H^2 L \tag{6}$$

and

$$\frac{dW}{dL} \propto 2 LH \frac{dH}{dL} + H^2 = 0$$

maximum work, or

$$2 L \frac{dH}{dL} + H = 0 \tag{7}$$

By differentiating (3) and (4) with respect to L and substituting in (7) we get the same relation given in equation (5).

Mr. Frank Fowle has described certain investigations made by him on telegraphic relays which resulted in securing greater force by means of enlarged poles, but I believe that, generally, designers have not given sufficient attention to this point.

There is another relation that I have found most useful, and that is—what diameter of core should be used to get maximum force when the air gap is inside the coil and the outside diameter of the coil is fixed and the heating in the coil is a constant.

Oliver Heaviside, in his "Electrical Papers," Chapter XVII, page 103, gives the relative diameters of core and coil as

$$\frac{y}{x} = \frac{\sqrt{5} - 1}{2} \tag{8}$$

where y is the diameter of the core and x is the outside diameter of the wire winding, but not including the outside wrapping.

In this equation no allowance is made for space between the winding and the core. My practise is to allow 0.2 inch on each side of the core. With this constant inserted, the equation becomes

$$x = \frac{1}{2}y + \sqrt{(y + 0.4)^2 + \left(\frac{1}{2}y\right)^2} \tag{9}$$

As an approximation correct within a small percentage I use the following:

$$\frac{x - 0.4}{y} = 1.6 \tag{10}$$

It is interesting to note that values of 3.6 for x and 2 for y satisfy both equations (**9**) and (**10**).

In these equations μ is supposed to be constant.

C. R. Underhill (by letter): The method described by Dr. Burrows for finding the magnetizing force along the axis of a solenoid is simple and very interesting. It is stated on page 483 of the paper that the calculated values are only approximate. Therefore, a comparison of the values obtained by Dr. Burrows's method and those obtained by the approximate method of the author will be of interest. In the following table are shown the ratios which are obtained by dividing the author's values in Table II of the paper by those calculated by the method of Dr. Burrows.

Section of reference a	1	2	3	4	5	6	
m							
1	1.12						
2	1.06						
3	1.05	1.025	(middle section)				
4	1.05	1.02					
5	1.05	1.02	1.017	(middle section)			
6	1.045	1.02	1.015				
7	1.045	1.02	1.015	1.012	(middle section)		
8	1.045	1.02	1.015	1.012			
9	1.045	1.02	1.015	1.012	1.011	(middle section)	
10	1.045	1.019	1.015	1.011	1.011		
11	1.044	1.017	1.013	1.011	1.011	1.01	(middle section)

Anyone wishing to work closer than one or two per cent should, therefore, calculate the values by Dr. Burrows's method. Those engaged in practical design can use the data directly from the curves in Figs. 15 to 24, because it is impossible, with the present known methods, to predetermine the pull between a solenoid and plunger at all points in its travel, with a greater accuracy than several per cent. The values for the end sections are of little importance because a long-range solenoid usually consists of more than two sections.

As to the demagnetizing action of a solenoid on its plunger, this is briefly touched upon at the bottom of page 480 and again on page 501 of the paper. For all practical purposes, the core or plunger can be assumed to be very long, and the demagnetizing action ignored for ordinary flux densities. The demagnetizing effect is only noticeable when uneconomical magnetizing forces are used. Fig. 25, page 496, shows this. The plunger was thoroughly saturated with 10,000 ampere-turns, and at this value the demagnetizing effect is scarcely noticeable. Even with 20,000 ampere-turns it is not serious. As the magnetizing force is increased, the plunger is saturated for greater portions of its length, so that when abnormal magnetizing forces are used the effect is noticeable.

The author's reference to the important law of Mr. Carichoff, which is based on the assumption of no leakage, was given to emphasize the importance of magnetic leakage in all electromagnets of the plunger type, since the leakage increases the flux in the plunger and, consequently, the pull. In electromagnets of the horseshoe type and modifications of the same, the pull due to magnetic leakage is lost because the relative positions of the coils and cores are unfavorable, and, furthermore, they are usually fastened together.

The characteristics of alternating-current electromagnets are easily explained when magnetic leakage is considered. Many otherwise excellent papers and articles have been written upon the subject of electromagnets, but, in nearly all cases, no leakage is assumed: consequently, their value is lessened.

The characteristics are best predetermined from the standpoint of energy, but, until the permeances of the leakage paths for different positions of the plunger are thoroughly worked out, only the average mechanical force or pull can be calculated, and this is of little use to designers of electromagnets, excepting in the design of electromagnetic hammers and the like; it does not throw light on the mechanical forces or pulls at all points throughout the entire range of travel of the plunger, and the latter is usually a very important consideration.

Presented at the 294th meeting of the American Institute of Electrical Engineers, Washington, D.C., April 24, 1914, under the auspices of the Electrophysics Committee.

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SOME INVESTIGATIONS ON LIGHTNING PROTECTION FOR BUILDINGS

BY L. A. DE BLOIS

ABSTRACT OF PAPER

A description is given of investigations conducted for a large manufacturer of explosives to determine upon a suitable system of lightning protection for buildings containing explosives. The work is divided into the following sections:

(1) An analysis by oscillograph of the secondary currents induced by actual lightning discharges in vertical earthed conductors, the results seeming to indicate that such currents are non-oscillatory and aperiodic, though occurring in either a negative or positive direction. An attempt is made to explain the phenomena generally attributed to high, frequency oscillations by the existence of unidirectional waves of almost vertical front.

(2) An investigation of the primary effects of a 20-in. spark in air, having the same essential characteristics as those attributed to lightning, when applied to a model protective system consisting of isolated vertical conductors surrounding a small building.

(3) An investigation of the secondary effects produced under the above conditions, which are considered to be static inductive rather than dynamic inductive.

A brief description is given of a general protective system recommended for explosives buildings.

IT IS the purpose of this paper to describe the results of a study made in an effort to develop a system of lightning protection for explosives manufacturing buildings and magazines which would insure at least some measure of protection, rather than a possible increase in risk—as unfortunately seems to have been the case with some so-called "protective systems." Since such systems have been based on speculative theory as to the actual character of lightning or on the behavior of model buildings when subjected to spark discharges supposed to bear close relationship to the natural phenomenon, an effort was made to obtain, if possible, some further and more dependable information, that would furnish not only a better understanding of the actual conditions to be met, but also permit more reliable reduced-scale laboratory experiments.

Investigation of Lightning Discharges

Secondary currents induced in vertical earthed conductors by the passage of nearby lightning discharges to earth presented themselves as a possible clue to the nature of the current in the actual discharges. Two 103-ft. (31.3-m.) wireless towers, situated on the roof of a 123-ft. (37.4-m.) office building, were utilized. The yards, 170 ft. (51.8 m.) apart, subtended a horizontal plane area of 5100 sq. ft. (469 sq. m.) represented by 21 horizontal and approximately parallel conductors. This large plane area, acting as condenser against the upper air, was found necessary in order to permit the reception of induced currents of sufficient magnitude for analysis by the instruments available. The conductors were divided into two groups of 19 and 2, to serve as " collector-aerial " and " pilot " respectively, each set being cross-connected at the ends and provided with two 180-ft. (54.8-m.) leads running obliquely downward to the laboratory on the roof. The leads were provided with horn arresters just outside the building and were connected on the inside to switches operated by ropes. This arrangement of aerials gave an excellent installation, well above the ground, with an unobstructed view of the country in all directions; thereby insuring freedom from wave-absorption by grounded conductors nearby. A ground connection was secured by a heavy cable bolted to the steel framework of the building. The natural wave length of the " collector-aerial " was found to lie between 700 and 800 meters.

The instruments used consisted of a wireless receiving equipment with various detectors, an indicating " ceraunoscope " (needle detector with electric alarm decoherer), an adjustable spark-gap, an 800-volt multicellular static voltmeter, and a double-element permanent-magnet oscillograph, modified by the addition of field coil and motor drive for the revolving mirror. The wireless equipment was used on the collector-aerial for storm prediction as described later, the " ceraunoscope " and static voltmeter between the pilot-aerials and ground to indicate respectively the occurrence of heavy discharges and the variation in static potential, the spark-gap between either aerial and ground as an alternate method of indicating the passage of discharges, and the oscillograph between the collector-aerial and ground to furnish a means for analyzing the induced currents. The low resistance, inductance and capacity factors of the latter instrument rendered it satisfactory for this purpose when the

usual gold-leaf fuses were replaced by solid metal. Its periodic time (5000-6000), on the other hand, would have been too low to permit the measurement of high frequencies, had they been encountered.

The importance of storm prediction by the wireless equipment was emphasized by the necessity of recording all the comparatively few discharges which were sufficiently heavy or sufficiently close to induce measurable currents in the aerials, a condition aggravated by the transitory nature of the storms and by their comparative infrequency. As a matter of fact, of fourteen electrical storms in the summer of 1913, only six were of a character suitable for observations, and the period during which such work could be performed averaged less than twenty minutes. It was found that after some experience with the sound produced in the wireless receivers by the waves propagated by lightning discharges, the presence of an electrical storm could be predicted from 8 to 10 hours before its possible advent, and hourly observations on their intensity would generally indicate whether it was approaching or merely passing through the field of the instruments. Assuming a rate of storm-travel of 25 to 40 miles (40.2 to 64.3 km.) per hour, it would thus seem possible to detect the presence of a traveling storm between 200 and 400 miles (321 to 643 km.) away.

Until the storm was close at hand, differences of potential between collector-aerial and the ground occurred only coincident with distant flashes of lightning, but were often sufficient to jump a small air-gap or administer a sharp shock, unless the wires were grasped firmly in the hand before the switch was closed. As soon as the edge of the storm clouds was nearly overhead, however, the aerials when disconnected from ground commenced to assume strong static charges, as indicated by the static voltmeter or spark-gap. Such charges always occurred with electrical storms, though less prominently where inter-cloud lightning prevailed, and also often occurred with cumulus clouds that gave no other indication of their electrical character. In such cases the aerials acted as condensers of low capacity charged to high potential, and if connected to ground through the oscillograph, discharged at the natural frequency of the circuit. As this was approximately 400,000 per second, while the natural period of the oscillograph was only 5000-6000, such discharges did not affect the elements, though the addition of series inductance rendered them clearly visible on the revolving

mirror. If the spark-gap was substituted for the oscillograph at such times, sparks of discharge passed fairly uniformly for considerable periods until a lightning stroke took place, when they succeeded each other so rapidly as to resemble momentarily a single arc of some duration. At such times the static voltmeter on the " pilot " aerial departed from its usual slow swinging variation by a sudden upward swing, sometimes from zero and sometimes preceded by a gradual rise. This was generally followed by a momentary subsidence to zero.

The first attempts to use the oscillograph for indicating currents induced by lightning discharges during 1912 were not encouraging, no indications being obtained, mainly on account of insufficient capacity in the aerials, but after considerable practise with the instrument on high-frequency discharges, and various modifications in the aerials and apparatus, visible indications on the revolving mirror were noted during the first storm of 1913. These were obtained only during the passage of heavy discharges comparatively close to the laboratory. With especially violent discharges the static voltmeter on the " pilot " aerial often arced over, as well as the oscillograph switches, and in several cases, the horn arresters outside the laboratory. The handling of the equipment had to be done by means of well-insulated poles, or only after first disconnecting and grounding the aerials—in fact the whole work of observation was far from pleasant, especially at night, the noise of the thunder and rain being often deafening and accompanied by numerous sparks in the apparatus, and at times by sharp hissing brush discharges presumably from the building itself, and the general discomfort was increased by the possibility of interruption to the lighting service and power supply from induced effects. All these conditions naturally contributed to the difficulty of securing permanent and conclusive records.

As the collector-aerial could not be tuned to the incoming wave, and responded only with forced oscillations, great difficulty was encountered in obtaining sufficient induced currents for satisfactory indications, except in the case of unusually heavy discharges nearby. Otherwise, the photographic records were exceedingly minute, and were moreover obscured by a heavy zero-line, resulting from the continuous rotation of the oscillograph film at high speed for the prolonged period necessary to insure the reception of a record—there being of course no means of foretelling the occurrence of a heavy discharge. Consequently

visual observations on the revolving mirror were found to be more satisfactory, though of course producing no confirming records.

In August 1913 a storm of unusual duration and intensity occurred and for a time appeared to be central over the locality. Three photographic records in particular were obtained, which are reproduced in Fig. 1 as largely typical of the lesser records obtained previously.

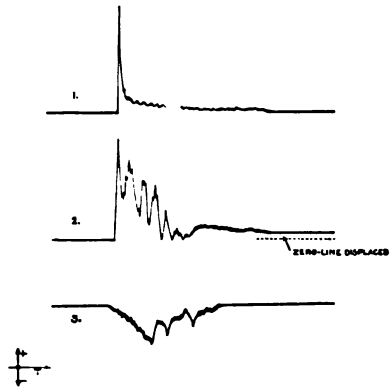


FIG. 1—LIGHTNING OSCILLOGRAMS STORM OF AUGUST 23, 1913

Referring to Fig. 1, curve (1) is a typical example of a single steep-front discharge from clouds to earth. The rate of initial rise of current is too rapid to be figured with any accuracy from the record. The maximum value of the induced current as recorded on the film was 0.5 ampere (actually probably exceeding this amount), and the peak proper endured 0.0008 sec. The latter part of the decay of the current endured 0.02 sec., giving indications of minor sustained oscillations above the zero-line, occurring with a periodicity of about 15,000 per sec. This effect is unmistakable and, though not previously photographed, had been noted in a few of the discharges observed on the revolving mirror.

Curve (2) is a typical steep-front wave with five main and three supplementary peaks, of which the values are approximately as follows:

	Maxima, Amperes	Duration, Seconds	Resultant Minima, Amperes
1st Peak	0.474	0.0005	0.225
2nd Peak	0.387	0.0015	0.114
3rd Peak	0.305	0.0016	0.069
4th Peak	0.266	0.0014	0.010
5th Peak	0.152	0.0012	0.000
	Total	0.0062	

These peaks are followed by a gradual rise to 0.042 amperes with indistinct indications of sustained oscillations of a higher

periodicity than in (1) for 0.01 sec., gradually dying away to zero. The total duration of discharge was 0.0184 sec.

Curve (3) is a wave of totally different character. The direction of flow is from the earth upwards, but with a gradual rise with indications of oscillations to a maximum of 0.18 amperes, which is reached in 0.0046 sec. The current then starts to decay but in 0.0023 sec. is interrupted by a sudden peak of 0.121 amperes, and again in 0.0025 sec. by another peak of 0.069 amperes. The total duration is 0.0129 sec.

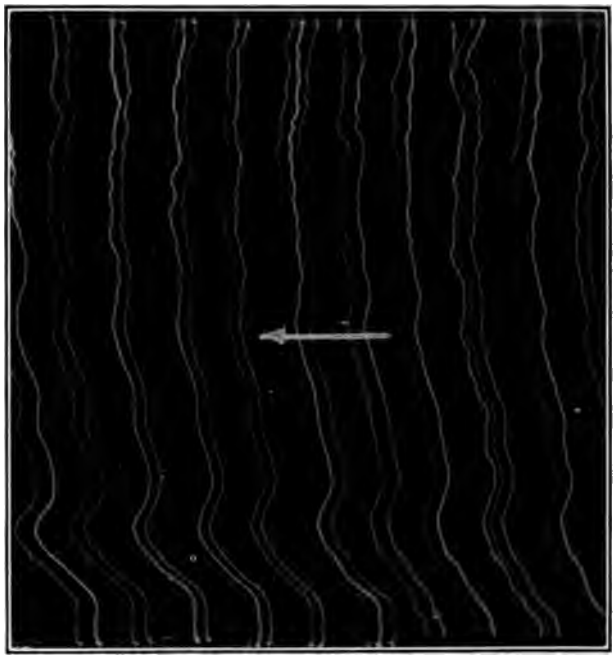
A summary of all other photographic records is as follows:

Total number of separate discharges recorded photographically	50
" " " " " with single peaks	38
" " " " " " multiple "	12
" " " " " " steep wave-front	29
" " " " " " sloping " "	21
Total number of strokes positive (from clouds to earth)	43
" " " " negative (from earth to clouds)	7

Average duration of 38 single peaks	0.00065	sec.
Minimum " " single peak	0.0002	"
Maximum " " " "	0.0016	"
Maximum duration of multiple discharge	0.0034	"
Maximum number of peaks in one discharge	6	"

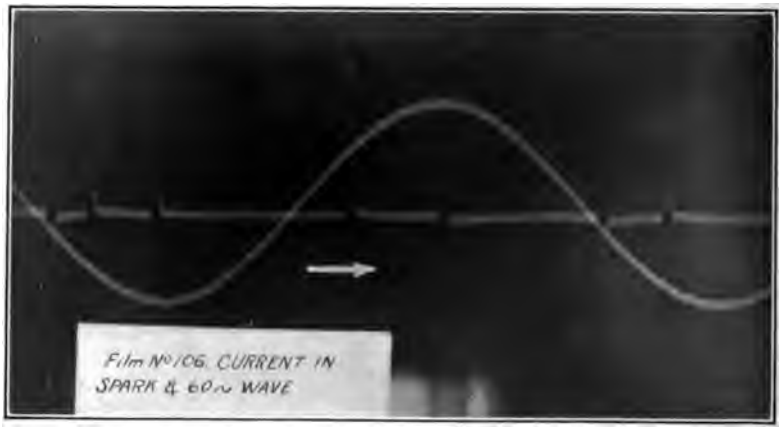
In this tabulation the three heavy discharges (1), (2) and (3) already discussed in detail are not included, as their measurements were not altogether comparable with the lesser indications obtained during the previous storms. For instance, the single-peaked steep-front wave (1) showed a total duration of 0.0208 sec., but of this the peak only would have been observed in the smaller records. This peak actually endured 0.0008 sec., which agrees fairly well with the average duration of 0.00065 sec. found for the 38 single-peak waves, and we may assume that each of the latter may have had its own prolonged decay similar in general respects to that of (1), but which was obscured by the broad zero-line of the oscillogram.

In no records was there any indication of regular periodic high-frequency oscillations in the induced current. Had they existed, the oscillograph, of which the periodic time was 5000 to 6000, would have failed to respond. This was never the case with heavy discharges to earth nearby, though it did happen, presumably for other reasons, with many purely inter-cloud discharges. Moreover, the static voltmeter could hardly have been expected to respond to high-frequency oscillations as it did in the majority of cases of lightning discharges to earth. On the other hand, it is probable that the currents induced



[DE BLOIS]

FIG. 2—PHOTOGRAPH OF 20-INCH SPARK WITH REVOLVING CAMERA



[DE BLOIS]

FIG. 3—OSCILLOGRAM OF CURRENT IN SPARK FROM OSCILLATION TRANSFORMER SECONDARY

in the collector-aerial followed in a general way at least the variations in the traveling waves of the lightning discharges, since such variations, judging by the oscillograms, involved high values of $\frac{di}{dt}$ only in the case of steep-front waves, and also for the reason that the damping effect of the aerial, whose natural period of vibration was about 400,000, must have been very small. If such was the case, do not the records obtained point to the fact that lightning discharges are essentially unidirectional, non-oscillatory, aperiodic phenomena, especially since the steep wave-front occurring in the majority of such discharges would account for all the usual effects attributed to high-frequency oscillations?

A point in doubt is a suitable explanation for the occurrence of multiple peaks, as in 2, and for the gradual rise of current, as in 3. In the former case, the time intervals between maxima are too short to allow the peaks to be construed as the so-called " related discharges " which are photographed as a single flash by a stationary camera, but as separate discharges along the same path by a camera slowly rotated in the horizontal plane, notably in the work of Dr. B. Walter. Since the current rarely reached zero between maxima, these peaks may represent simply the result of the " progressive break-down " of the atmosphere so clearly defined by Dr. C. P. Steinmetz, that is, of a discharge from point to point. On the other hand, the slow rise of current as in (3), may correspond to the *A* discharge of Sir Oliver Lodge, brought about by the gradual building-up of potential, possibly accompanied by the formation of brush discharges from buildings, etc., brilliant examples of which were noted in the storm during which these oscillograms were taken, or by the formation of striae gradually lengthening and preparing the discharge path. If such were the case, conversely, the *B* or " overflow discharges " of Lodge might correspond to the steep-front waves. It should also be observed that the total duration of discharges as figured from the oscillograms seems greater than usually assumed on the basis of high-frequency effects, and consequently the actual discharge current may be somewhat less than generally assumed on the basis of dynamic effects.

Whatever may be the true explanation of such points as these, it seems reasonable to assume that the most dangerous discharges are those with almost instant rise to maximum value, both

on account of the impact of the stroke and the possibility of dangerous secondary effects.

Investigation of Primary Protection

For the laboratory work a loose-coupled oscillation transformer was used with Leyden jars and rotary spark-gap, energized by a three-kw. 60-cycle magnetic leakage type transformer. Interruptions took place in the condenser circuit 527 times per sec., and a 42-in. (1.07-m.) spark of good substantial character was obtained from the secondary transformer terminals, though for practical purposes this was reduced to 20 in. (0.5 m.) during the greater part of the work. Fig. 2 shows photographs of this spark taken with a revolving camera, indicating the occurrence of groups of sparks for each half-wave of the 60-cycle supply, while Fig. 3 shows an oscillogram of the current in the discharge. This consists of one main half-wave, either positive or negative, with steep front and with an average duration of 0.00046 sec., followed by one or two suppressed half-waves. This agreement with the oscillograms of lightning discharges in the matter of steep wave-front and short duration was considered sufficient excuse for the employment of the 20-in. (0.5-m.) spark in the work to follow. It might be added that the discharge presumably corresponded to Lodge's *B* type, that is, was produced suddenly and not by a gradual building-up of potential, and in conformance with this struck equidistant ball and point electrodes impartially.

Preliminary work with this spark, directed vertically downward from points (called "cloud-points") pendent from a suspended metal "cloud", to a metal ground-plate or a box of dry or moistened earth on which was placed the model of a small building constructed of pasteboard with metal roof and interior metal apparatus, pipe lines, electric lines, etc., on a scale of 1 in. to 20 ft., with four isolated vertical lightning rods placed a short distance from its corners, led to the following general conclusions, some of which are of course self-evident:

(a) The building was in the greatest danger when the discharge took place from one cloud-point placed directly above it.

(b) The lower this cloud-point, the more likely the building was to be struck, especially if the lightning rods were low or widely separated.

(c) An increase from one to four cloud-points merely increased the number of rods likely to be struck simultaneously.

(d) The closer the cloud-point to the building, the greater the number of rods which were likely to be struck simultaneously.

(e) With one cloud-point, the farther apart the rods, the fewer were struck simultaneously.

(f) With outside lightning rods of a proper height and at a proper distance, a model similar to the one tested could be protected with apparently 100 per cent efficiency.

(g) With low or widely separated rods the introduction of a metal roof, not grounded, seemed to increase slightly the probability of the building being struck, and at the same time seemed to increase the probability of more than one rod being struck simultaneously.

(h) Grounding the roof, if the protection was poor, seemed to increase the probability of its being struck, but if the protection was good such grounding seemed to have little or no effect.

(i) The introduction of an intermediate cloud below the main cloud seemed to render one rod more likely to be struck if the intermediate cloud was high, but when low this effect was more or less neutralized.

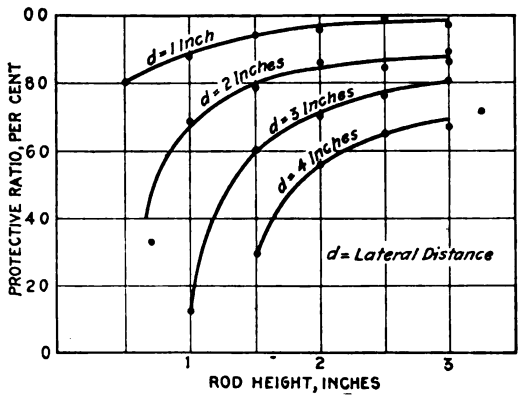


FIG. 4—ROD EFFICIENCY—EFFECT OF HEIGHT AND SPACING

(j) While a horizontal plate or a mesh screen across the tops of the rods gave perfect protection, a girdle, when the rods were too widely placed or too low, was not entirely effective.

These conclusions, though based on a length of discharge equivalent to only 700 or 800 ft. (213 or 243 m.), furnished the necessary information for the arrangement of apparatus in the following tests, which will be summarized as briefly as possible and discussed in detail later.

Protective Efficiency of Outside Rods. Four small vertical wire rods of equal length were set up symmetrically on a metal ground-plate, equidistant from a central rod which represented the object to be protected and was adjusted until its height was just sufficient to avoid being struck by any of the discharges from the cloud-point directly above. This height expressed

as a per cent of the height of the outside rods was termed the "protective ratio" of the latter, and is plotted in Fig. 4 for a fixed cloud-point height of 20 in. (0.5 m.) above the ground-plate with varying rod-heights and lateral spacing from the central rod, and in Fig. 5 with varying cloud-point height for different combinations of rod-height and lateral spacing.

Effect of Imperfect Grounding of Rods. The four outside rods were raised so as to leave slight air-gaps between them and the ground-plate. This was tried for different rod-heights and air-gaps, but the effect on the protective ratio was almost exactly equivalent to that produced by cutting off from the tops of the rods an amount equal to the length of the air-gap.

Effect of Conductivity of Rods. A long series of tests was

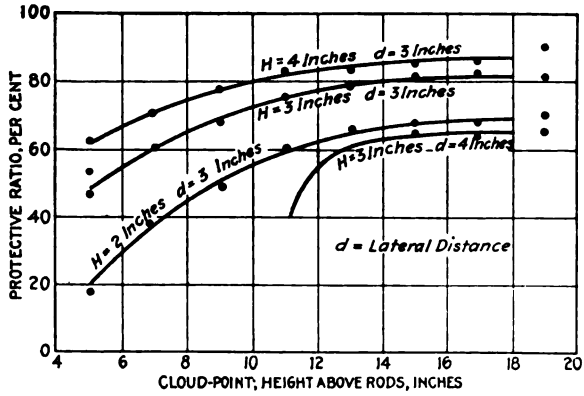


FIG. 5—ROD EFFICIENCY—EFFECT OF CLOUD-HEIGHT

made with rods of different materials, of different diameters, and with rods in which were inserted small inductances. The protective ratios of good conductors such as wires of different metals of various diameters were almost identical, and even the insertion of inductance, with and without iron in the magnetic circuit, did not seriously affect their efficiency. Poor conductors, however, such as green and dry wood, wood moistened with water, acids, etc., or rendered partially conducting by a lead pencil mark or by a carbonized streak resulting from a previous discharge, though frequently struck, failed to consistently protect any low object in their vicinity—even the ground-plate itself. Also, in contradistinction to good conductors, when struck they arced over for their entire length,

wood being splintered and eventually ignited after the moisture and volatiles had been driven off or consumed.

Discussion of Results. The function of a lightning rod is presumably two-fold:

(1) To form a projection from the surface on which the lower charge resides, extending sufficiently above the objects to be protected, and thus present to the clouds a salient point having the same relative potential as the lower surface.

(2) When struck, to carry off the current of discharge without potential differences in its length sufficient to cause the discharge to split off or be diverted to nearby objects.

As regards the first function, it is evident that the rods, in order to maintain the same potential as the lower surface, must be of conducting material and should be preferably in direct electrical contact with that surface. Their conductivity and potential relation should be such as to permit their following sudden, in fact, precipitous variations in the potential of the lower surface and therefore should not involve any appreciable time-element, as might be the case if high inductance or capacity were introduced. Aside from this, a high degree of conductivity would seem unnecessary. Poor conductors, on the other hand, such as dry wood, green wood, or wood with small wetted perimeter, though they might be struck in the natural course of events and the discharge follow along their surface in preference to a path of higher resistance through the air, would show no consistent protective ratio, as was the case in the tests on different materials and as seems to obtain in nature for trees.

In order to fulfil the second function, high conductivity with low inductance seems imperative, though, where isolated rods could be used, the effect of lateral spacing should be considered; thus if the distance from rod to building was as great as the height of the rod, it would seem that a rod of the minimum resistance to resist fusing could be used.

As regards protective ratio, it seems probable that the rods are nothing more than shunt-paths for the building and its interior equipment. If the latter is in direct contact with the lower surface of charge, the rods should also be in such contact or should be increased in height somewhat more than the equivalent distance. Theoretically the former seems preferable, as one would be led to believe that rods not in direct contact with the lower surface, though of good conductivity, might under some circumstances lag behind the changes in potential of the lower surface and so suffer a loss in efficiency, though

this was not borne out by the tests on the effect of imperfect grounding. On the other hand, it is uncertain exactly what the lower surface of charge is. It is presumably not the earth's surface, unless wet; it may be the surface of permanent moisture, though well-authenticated cases of discharges passing down mines, deep wells, etc., seem to point to the existence of even lower charges; in any case it is probably of good conductivity, as there seems to be no evidence of "inter-earth"—corresponding to inter-cloud—discharges.

The curves for protective ratio tend towards a constant value independent of cloud-height, seeming to indicate that only the lowest part of the path of discharge is affected by the rods. The geometrical relation between the length of the discharge path from the cloud-point to the building and from the cloud-point to the rods is given by the formula

$$H_r = \frac{d \tan a}{2} + H_b$$

where H_r = height of rod in feet.
H_b = height of building in feet.
d = lateral distance from highest point of building to rods, in feet.
a = angle subtended from cloud-point by rod and highest point of building.

This obtains only for small values of (a) but was found to agree with the experimental results by the addition of a constant $K = 0.11$, making the formula

$$H_r = d\left(\frac{K + \tan a}{2}\right) + H_b$$

It seems applicable to the condition of four rods surrounding a building where d = or $< H_r$. It should be noted that it involves no factor for cloud-height other than in the angle (a) and therefore indicates that the results of laboratory tests on protective ratio, etc., might be applicable to natural conditions if the scale of reduction was observed.

Probability of Being Struck. To test the efficacy of the usual argument that lightning rods "attract" lightning and so increase indirectly the danger to the building, a long series of tests were performed directly to scale, on a basis of a minimum length of lightning discharge of 3000 ft. (914 m.) in mountain-

ous districts. Very small models of the building selected (48 by 32 by 41 ft. or 14.6 by 9.7 by 12.4 m. actual) were placed centrally on a cardboard target representing a circular area of 600 ft. (182.8 m.) radius, and this on a somewhat larger ground-plate with cloud-point directly above. The "probability of being struck" was considered to be the number of discharges that fell entirely or in part on the building, lightning rods or within the area subtended by the latter, and was expressed as a percentage of the total strokes falling within the 600-ft. (182.8-m.) radius.

Summarizing the results, it would seem that the erection of a building of non-metallic construction of the size in question, without contents, increased the danger to the plane area only slightly (4 per cent)—until the building was wet, when the "probability of being struck" was increased 32 per cent (net). If a metallic building was erected instead, the "probability of being struck" was increased 58 per cent, or if the building was grounded, 62 per cent. When metal apparatus was installed in a non-metallic building the "probability of being struck" was increased 12 per cent to 50 per cent depending on the height of the apparatus, and if the apparatus was grounded 26 per cent was added in the case of the lower equipment but apparently nothing in the case of the higher equipment. On the other hand, the addition of a short metal ventilator to the grounded apparatus increased the "probability of being struck" 30 per cent more.

When a metal roof was added to a non-metallic building containing metal apparatus the "probability of being struck" increased only slightly, whether the building was wet or dry, but when this roof was grounded, the "probability of being struck" was increased 12 per cent to 56 per cent, depending (inversely) on the height of the grounded metal apparatus inside.

With a non-metallic building with non-grounded metal apparatus and four outside lightning rods 70 ft. (21.3 m.) high and located about 50 ft. (15.2 m.) from the corners of the building, the "probability of being struck" was increased 38 per cent to 54 per cent, depending on whether the building was wet or dry. With a grounded metal roof installed, the "probability of being struck" was increased only 12 per cent, and if the metal ventilator were installed the net increase in "probability of being struck" would probably have been even less.

It is these latter conditions that are of particular interest in determining how much the danger from lightning to the building in question, which was of non-metallic construction, was increased by the erection of rods and apparently in this case the rods "attracted" about 10 per cent to 50 per cent more strokes. On the other hand, if the building had had a metal roof, if it were equipped with metal apparatus reaching nearly to the top, or if its exterior were wet with rain, the effect of the rods would be to add very little to the "probability of being struck." Moreover, it should be noted that these tests were made not only under the conditions of an isolated building on a plane area, but also with the cloud-point directly above the building—a combination very unlikely to occur in nature.

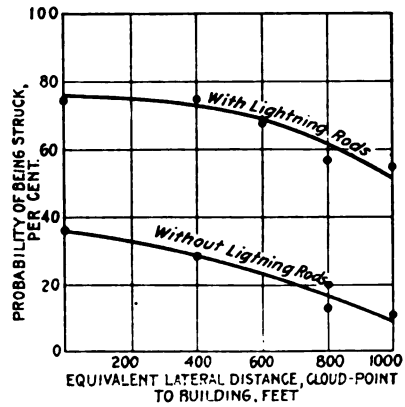


FIG. 6—PROBABILITY OF BEING STRUCK—EFFECT OF CLOUD DISPLACEMENT.

The effect of the position of the cloud-point is shown in Fig. 6, in which the "probability of being struck" is plotted against the horizontal distance from cloud-point to building.

INVESTIGATION OF SECONDARY EFFECTS

In order to reproduce secondary effects in a model building on a scale sufficiently large to be visible, an arbitrary standard of 1 in. (2.54 cm.) to 2 ft. (60.9 cm.) was adopted. This allowed the use of a model of sufficient size to permit the construction of interior apparatus with reasonable accuracy of detail, and, though the relative length of cloud discharge was diminished in proportion, it was felt that this, while increasing the intensity of static inductive effects, would not affect dynamic inductive

effects, since in any event the upper part of a vertical discharge would have little influence because of the narrow angle subtended by it. On the other hand, for dynamic inductive effects it was desirable to have the current of discharge as great as possible and the factor $\frac{di}{dt}$ as high as that of lightning.

The model building was constructed of wood with one side open and was completely equipped with metal apparatus, including pipe lines, electric lines, etc., extending for some distance outside, all metallic parts being separately removable and practicable to interconnect and ground. It was placed directly on an extensive ground-plate with the metal " cloud " above. Secondary discharges were noted by eye or by the use of a small exploring spark-gap.

Static Inductive Effects. Tests were made without direct discharge other than brush from the cloud. Secondary brush and spark discharges were noted inside the building and the following somewhat obvious general conclusions were reached:

(a) All conducting surfaces not thoroughly grounded, when exposed to the influence of a charged cloud immediately overhead, acquire a potential against ground which increases with the height of the conducting surface above ground.

(b) A difference of potential will exist between all conducting surfaces not bearing the same average spatial relation in the electrostatic field to ground or to nearby grounded objects. Such average spatial relation is determined by their shape and size as well as distance from ground or grounded objects.

(c) Conducting surfaces in a vertical plane which would acquire practically no potential from their position in the electrostatic field may acquire a charge from the influence of adjacent objects.

(d) The grounding of a conducting surface generally increases the danger of sparks from adjacent non-grounded surfaces.

(e) Interconnecting adjacent conducting surfaces can prevent differences of potential between them but may increase the tendency of the lowest surface (relative to ground) to arc to ground.

(f) Discharges tend to take the shortest path, and large surfaces in the horizontal plane should be interconnected or grounded at more than one point.

(g) A grounded roof acts as shield for objects beneath it and even when poorly grounded diminishes the potential between them, but potentials can be introduced below it by conductors which extend inward from the outside, provided they are of sufficient capacity.

(h) Secondary discharges may occur from the sudden charge of an overhead cloud or from its discharge. The discharge in any case follows the natural frequency of the circuit and consequently may become oscillatory, though this condition is improbable in the ordinary interior apparatus, excepting only electrical equipment.

(i) The effect of adjacent lightning rods is to diminish the intensity of secondary effects, though for outside rods of reasonable height and spacing, the "secondary static protective ratio" is practically inconsiderable.

Dynamic Inductive Effects. Tests for such effects were made both with the discharge from the secondary of the oscillation transformer and with the primary current of the latter carried down a vertical rod close to the model building. In the latter case the current was calculated to be approximately equivalent to a lightning discharge of over 100,000 amperes maximum value with a half-wave duration of approximately 0.000005 sec. —a condition far more severe than any indicated by the oscillograph storm-records. In no case could dynamic inductive sparks be obtained, though occasional static sparks were produced in unbalanced partially closed loops. This failure was attributed to the comparatively small area of the partially closed loops formed by the various equipment and by the fact that neither these loops nor vertical conductors could be "tuned" to the magnetic waves and consequently responded only with forced oscillations. When it is considered that with a high aerial of large capacity such as described in the first part of this paper, currents of only a fraction of an ampere were obtained with comparatively nearby discharges, it does not seem unreasonable that the dynamic inductive effects in a small model building should be insignificant as compared with the static inductive effects.

General Recommendations for Protective Systems

As a result of this work, the general recommendations for the protection of manufacturing and storage buildings where such protection is justified either by the impracticability of the operators always leaving the building during a storm, or by the value of the building or the character of its contents, consisted in a series of vertical isolated rods of iron pipe placed outside and surrounding the buildings, and grounded to annular conductors buried in the earth at least as low as the water pipes, with extensions running out radially at the corners; metallic roof projections such as ventilators to be eliminated as far as possible; metallic roof and floor coverings to be grounded at their salient angles; overhead pipe-lines and other metal conductors to be grounded at intervals and also where crossing the annular conductor; lightning arresters for outside electric lines and also for the lowest points of the building wiring (to remove

static charges); complete interconnection and grounding of all metal objects in the interior.

This paper has been prepared for the purpose of stimulating discussion and further investigation along similar lines, rather than for the advancement of any new theories. Others, for example, Sir Oliver Lodge and Prof. Elihu Thomson, have already pointed out that lightning discharges may be non-oscillatory and yet produce all the effects that seem to have led to the assumption that they are oscillatory in character. As for the laboratory investigations, both on primary and induced effects, it is recognized that these could have resulted in further and more certain conclusions had they been pursued with the aid of larger apparatus—such as is probably readily available to others, and to these the hope is expressed that they may become further interested in the investigation both of lightning discharges and of sparks produced artifically in the laboratory, as well as their interrelation with its bearing on the protection of buildings.

DISCUSSION ON "SOME INVESTIGATIONS ON LIGHTNING PROTECTION FOR BUILDINGS" (DEBLOIS), WASHINGTON, D. C., APRIL 24, 1914.

E. E. F. Creighton: There has been very little work done on the direct study of cloud lightning, and therefore this paper may be considered as a turning point. There is no committee at the present time of the American Institute of Electrical Engineers or of the National Electric Light Association which will give this subject the study that is needed. Perhaps the problem is important enough to receive the attention of the Bureau of Standards, and it would be an excellent one for that bureau to take up. It requires not only an organization of trained laboratory men, but also men who can develop instruments as they are required by the conditions that become apparent.

One very important point that has been discussed many times is the natural frequency of the lightning stroke. A great many of the great scientists of the world have discussed it—I think Professor Thomson has given a number of discussions on it, and also Dr. Steinmetz, and the matter is still held in abeyance. I do not think that the work done with the oscillograph can prove either that the frequencies are high or are low, because the oscillograph will not respond to these high frequencies, although it will respond to the summation of them. I have obtained instances of summation in the laboratory with five million cycles per second. This discharge through the oscillograph gives a deflection. Of course, what was produced in the oscillograph was the summation of the oscillations, giving the resultant quantity of electricity that had passed through the bifilar vibrator. Theoretically, I think there is in some cases a high frequency, and practically, types of lightning arresters which are sensitive to high frequencies and not very sensitive to impulses, respond by discharging, showing that there is at times a high frequency in the lightning.

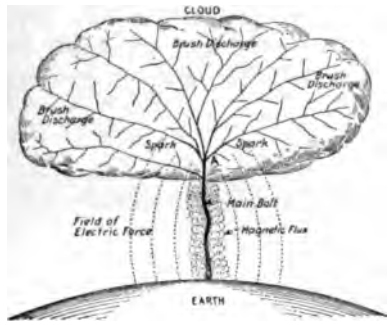


FIG. 1

Theoretical analysis of the cloud conditions, will, perhaps, illustrate what part of the discharge can oscillate and what part of the discharge cannot. Assuming that the electricity is freed at different points in the cloud, as shown in Fig. 1 herewith, there will be a brush discharge from different parts of the cloud toward one centralized point *A* that is failing, and as it approaches that centralized point there will be formed vapors of sufficient in-

tensity to be called spark discharge. Up in the outermost parts of the cloud the electricity is drawn through high resistance, and all the laboratory experiments show that this resistance is above the critical value which will allow oscillations. The conditions of high resistance exist even in those parts where the blue brush discharge is just turned to a definite bright spark discharge. But somewhere just above the point A, around the upper part of the main bolt of lightning, the resistance becomes very low. From this region down to earth there is a good conductor to transmit current, which is surrounded by magnetic energy, indicated in the sketch by rings around the main bolt. There is also a high voltage from end to end of the main bolt which gives electrostatic energy. These three conditions, electromagnetic energy, electrostatic energy and low resistance, will naturally produce an oscillation. Therefore I think there is an oscillation in the main part of the discharge path, but the discharge in the rest of the cloud could not possibly oscillate.

George R. Olshausen: I congratulate Mr. DeBlois on being successful in getting any registrations whatever with the oscillograph in the short period of time of twenty minutes in which this work was done. You must remember that we do not know when the lightning is coming, where it is coming, and when you bear in mind that we only have twenty minutes in the whole season to work in, I think it is very remarkable that Mr. DeBlois secured any results at all. He seems to think that these registrations cannot be the so-called related charges. Professor B. Walter, of Hamburg, first took pictures by means of a moving camera, and showed that, in general, the lightning stroke consists of a great number of parts, showing that there is a so-called predischarge which breaks down the air, first going part of the way, and then proceeding a little further, and finally a complete flash is made. This first flash usually heats up the air and makes it more conducting than before. After the first discharge there is usually a period of rest, and then there may be a gradual leaking of electricity along this heated part, which might make a continuous current for quite a long time, and then there may be a series of intervals and discharges, and finally there may be a closing flash something like the residual discharge of the condenser.

As to the period of the discharge, something can be said in both directions, that is, for the unidirectional discharge and also for the associated discharge. The experiments made by Pockels in determining the current of a stroke of lightning, by means of the magnetizing effect on prisms obtained from the mineral base salt, seemed to indicate that the flash is unidirectional, and occasionally that they were not magnetized at all, and in that case we may have been dealing with an oscillatory flash. Ende (*Electrotechnische Zeitschrift*) has made some calculations by means of the Maxwell equations on the frequency of a flash, and he comes to the conclusion that its probable frequency is some-

thing like 8000 oscillations per second. However, a great many assumptions are made in this calculation. One assumption, for instance, is in regard to the self-induction of such a flash. What is the self-induction of a circuit which is not closed? Hertz says there is no such thing as self-induction of a straight rod. Our ideas of self-induction, when applied to closed circuits, are not very well defined.

A. G. Webster: As to the conclusions in the paper, I agree with what has been said by the two preceding speakers. There is no doubt that Fig. 2 shows an oscillation there, but it has not been proved that there are any high-frequency oscillations. Whether there are any such, I do not know, and I do not suppose anybody else does, although Professor Thomson, in talking with me recently, admitted that he did not believe there were any high-frequency oscillations.

All that Dr. Olshausen said about the complication of the phenomenon is absolutely true. As Dr. Olshausen has said of self-inductance, I believe there is self-inductance here. But what is it? It is much worse to calculate than the reluctance of a solenoid. Everybody knows that, who has examined, experimentally, sparks in revolving mirrors. I have examined them for a good many years, and I believe, perhaps, I was the first to show the oscillatory character of such discharges in a lecture which I delivered in the Lowell Institute at Boston seventeen years ago. There is always at the start of the discharge something that does not come as regularly as the rest, that is, there is a breaking away which heats the air, ionizes it, and after that come the regular flashes—these come pretty regularly after that.

In this connection I think of a commonplace phenomenon which Professor Thomson will corroborate or disprove, because there is no one who makes more daily observations from just looking out and looking around than he does. I believe that it is very common for barns with hay in them to be struck by lightning, and I suppose the reason is that there is somewhere an upward current of hot air. As has been said, these lightning strokes have been blown about. In Fig. 2 of the paper, in the upper part of the photograph you see the discharge is not straight and in the lower part it has apparently been blown about very violently. We have been told to look out for current when it strikes. You cannot tell when a lightning stroke is coming, and you cannot dodge a lightning stroke. There are places where hot currents of air seem to make good paths for the lightning. Whether the heat resistance is above or below, it is hard to tell. If it is above, it will not be oscillatory. You engineers know what the resistance of a long arc is, and I am pretty sure that when the arc is gone, the resistance goes down very much, indeed.

As has been said, the whole thing is a good deal like a Hertzian oscillator, only the cloud is spread out some times for miles, and as you watch it you do not get as good observation as in revolving

machinery, but you get something. What Dr. Olshausen has said is true, it breaks away all over, and whether that is hard to see clearly or not, I do not know.

As I said; this photograph shows an oscillation. There is one thing which is evident, if there had been a different potential between the cloud and earth, or the free cloud, there would not be a lightning stroke. There must be a condenser, and in order to have a stroke it might empty itself out. You speak of the residual discharge in a Leyden jar, but you seldom find discharge going up the other way. The oscillograph will certainly show a current, if it does not burn out, or if something else does not happen to it.

Elihu Thomson: The results Mr. DeBlois has shown are, in a large measure, explanatory of what has been my impression for years, in fact, as long as I can remember having any thought or dealings with lightning or lightning protection. While it may be true that within the path of the discharge there may be oscillatory portions, I think the main phenomenon is that of a continuous current.

I arrived at that conclusion early in my investigations in this wise: I have been in telegraph offices when lightning struck at some place nearby, and have been near a telephone when lightning also was nearby, and I found that the relays went click, click, click. They acted as if they had received a direct current—no high frequency, pure and simple, would have induced such an effect in the relays; it would instead have jumped the relay and sparked across the terminals.

So, also, everybody knows that during a thunderstorm a telephone bell is frequently rung—which means that a current went through the numerous turns of the electromagnet. That could not be induced by high frequency, it was induced by a steep wave front and not obliterated by the reversal of the phase of the wave, as would be the case with high-frequency effect.

I quite agree with Mr. Creighton in the assumption that there may be in the length of a long discharge to earth some parts where there is oscillation, but if I were to picture the effect, as it occurs to me, it would be about as follows:

I will first make the statement that I do not think it is quite the thing to consider a cloud as a charged conductor. That statement I have made many times. It is not a conductor. It is a very poor conductor—it is a mass of fog. You cannot locate charges on it as you can on a tinfoil condenser. The cloud has plus or minus charges all through. They tend, naturally, to approach the earth, which has the opposite charge.

Somewhere in this system, perhaps where the cloud dips down a little, over an object on the earth's surface a little higher than the rest, there is a beginning of the breakdown. No doubt it begins as accumulation of a free charge and rapidly develops into a discharge. It discharges the lower part of the cloud, and as that begins to discharge, the rest of the cloud starts to feed into it, the cloud path ramifying like tree branches in all directions.

Many photographs, even the photographs shown on the screen a short time ago, show two other discharges in the same field, fine discharges, leading down this way and that; what are they? They are the perspective projection of the more or less horizontal discharges miles away in the cloud and feeding the main discharge.

I have one particular picture, which I wish I had brought along with me, which shows a tremendous discharge in the middle distance, and then down to the far horizon of the picture, from this main discharge point, there are branching discharges which apparently lead away in all directions. It is like a great tree, the branches feeding into one massive spark. Now, if that feeding distance is five or even ten miles, as it may easily be, then, the limit of rate of breakdown being the velocity of light, high frequency is forbidden. I mean by this that if the energy is to oscillate through the whole length of such a long path of discharge it cannot do so at a high frequency, for during a quarter wave it will need to travel say five miles. The highest possible speed is light velocity, and even at that speed the period is not above 9000 per second.

On one occasion I heard a thunder clap which had a true musical sound, like the sound of a bell. I was convinced in that case that it must have been a discharge of relatively low frequency, I should say not more than three hundred or four hundred vibrations per second.

I have been asked to state why it is that barns are struck by lightning so often, especially when they have moist hay, etc., in them. They are struck pretty often when they have no hay in them, and I do not know that the moist hay has much to do with it. If they are struck by lightning while the hay is in them, they may be burned; if they are struck by lightning when there is no hay in them, they may not be burned. Of course, the combustible material takes fire very readily. That may be the difference. But let us ask—why is the barn struck primarily? Because it has one of the best grounds that can exist. The ammonia salts, the drainage from the cows and horses, soaks into the earth, and that forms a direct connection to the earth. That is why the barn is struck. Why is a barn equipped with lightning rods, which take the charge directly to the ground, struck by lightning and destroyed? Because no conducting ground outside the barn can be compared to the splendid ground which exists inside the barn. We would naturally expect the lightning to go to the best conductor, the best ground on the premises. Let me emphasize this. It will take the best ground on the premises, and that is within the barn. The moral of it is that lightning rods should be anchored where the *best ground is obtainable, in all cases*—something which is quite generally forgotten in providing lightning protection.

I have very little confidence in investigations in lightning phenomena made with small apparatus like the ordinary static machine. In the first place, you cannot imitate a cloud, no mat-

ter how you try, you cannot get any representation of it, by any machine. Among others, Sir Oliver Lodge made some investigations in that way. He used a copper sheet to represent a cloud—mounted below it little rods of copper, iron, and different substances, and then concluded, because he got the snappiest spark with the copper, that copper was the worst material of which to make a lightning rod, and that iron was a very much better material. When we go back to the figures I gave before, and the photographs of lightning discharge I have considered which show a tremendous stroke of lightning falling on a house—the house is about 20 feet high—the spark runs up to the clouds, and ramifies in it miles away, we ask—What influence can a rod of copper or iron have on the character of that discharge; a few feet of rod on a few miles of spark? What is his conclusion worth, where the spark is miles long, and the lightning conductor is an almost infinitesimal part of the path?

In regard to the residual discharge of the Leyden jar, we have taken that to mean that a part of the charge soaked into the glass, and that when we discharged the jar there was need of time for the glass to deliver the soaked charge to the coat of tinfoil. This leaves a slight charge which can give a residual discharge. It depends on a known property of glass, called soakage. We have nothing of that kind in the case of lightning, necessarily.

It is very easy to understand, it seems to me, why with lightning we should observe repeated discharges down the same path. The first discharge establishes a fairly good conductor to ground and some other charged portion of the cloud, more distant, now finds it easy, as it were, to take up that path and discharge; but this will not be instantaneous. It takes some time, according to the velocity of light, for stresses to arrange themselves for the second discharge. Thus there is a slight interval before the charge reaches its full amount and takes the path opened by the first discharge.

W. J. Humphreys: There is one point I want to call attention to. I will not go into a discussion of the entire paper, though it is very interesting to me. This subject has interested me very much in the last three months. The point I have in mind covers one thing which has not been mentioned, as a possible evidence against the oscillating nature of the discharge. We will often find in a discharge of some kind or other, going down, where there are short breaks, secondary discharges going off from it in branches, just as we have in the case of the ordinary discharge between the terminals of an ordinary alternating-current machine. But when we examine these with a rotating camera we never find that they come back in that way, they are always going off in the same direction, whatever direction it may happen to be. You do not find succeeding discharges going in the opposite direction, which we might possibly expect—that we would have a discharge going first in one direction and then in the opposite

direction. In the case of the succeeding discharges, we will find in some few cases—in exceedingly few cases, but in some cases—that there will be a feeble discharge passing off in the same direction. Sometimes it may be that there go out directly a dozen branches in all. This shows, since the branching may occur a second and third time, that if you had them oscillating you could probably get them going that way, as well as this way, but you do not find that.

In the case of the lantern slides shown a short while ago, there is one particular point in regard to them that Dr. Olshausen understands possibly better than I do, but I have had occasion to study exactly the same phenomena. I feel convinced, with these two discharges that come down, one apparently being instantaneous and done with, and the other one that repeats itself, that the two start out in identically the same manner, and in the subsequent case the main branches break off and divide.

George R. Olshausen: I would like to say that these two discharges are entirely separate and the time between is 0.129 of a second. They have been calculated. They are not connected, they do not run down the same path. The time is calculated by taking a photograph with the stationary camera, and at the same time with the moving camera, and it is easy enough to calculate the time between the two flashes.

Professor Walter, of Hamburg, has photographed sparks having a frequency of 300,000 per second. The trouble with our lightning photography is that we have a flash which has a duration of a very short period of time, combined with high frequency, and in trying to photograph that we must be sure that the first registration is not wiped out by the successive flashes which may take place. We therefore must make our registration on a spiral, or something of that kind, so that when we think we have any evidence of oscillations they may not be wiped out by the succeeding flashes.

Trygve D. Yensen: A few years ago I became interested in an investigation conducted by Professor E. J. Berg of the University of Illinois to determine the character of lightning discharges. During this investigation a few preliminary experiments were conducted in the laboratory by discharging sparks from a static machine and Leyden jars through a circuit containing a resistance, an inductance and a condenser in series, each one being shunted by a spark gap. The spark gaps were adjusted, until the distances were found that corresponded to the voltages across the resistance, inductance and condenser respectively. The experiments showed that the voltage across the inductance was practically zero, while that across the condenser was beyond the limit of the apparatus. This result, after making numerical calculations, pointed towards a unidirectional discharge. Although these experiments were not conducted with refined apparatus, they confirm the results obtained by Mr. DeBlois.

The main part of the investigation was carried out with apparatus similar to the ones described above, but placed upon six separate poles, 40 ft. high, distributed 100 ft. apart in an open field. The recording apparatus were connected in series with lightning rods, thoroughly grounded and extending above the tops of the poles. This outfit has now been in the field for four years, and although lightning storms have been quite frequent, the only record obtained has been of minute discharges across the condensers. Not a single direct discharge to the rods has taken place. At one time a barn 2000 ft. away was struck by lightning and burned down, but even then the record obtained was only a small discharge across the condenser. Similar results were obtained from an outfit erected near my residence. Here the lightning rod was placed in a tall tree, extending 80 ft. above ground.

Although our experiences have been mostly negative, they may be of some value when considered in connection with the important results obtained by Mr. DeBlois.

L. A. De Blois (by letter): In preparing this paper the writer made no assertion that the current in all lightning discharges was unidirectional, but pointed merely to the fact that the comparatively few records obtained on the oscillograph seem to indicate that the currents in the particular discharges that occurred at that time were in the main unidirectional.

Mr. Creighton casts some doubt on the action of the oscillograph under high frequencies. It so happens that some special investigations were made by myself along these particular lines. I found that the oscillograph would respond ballistically to a Leyden jar discharge estimated at 3,000,000 cycles when passed across a spark gap into the instrument. On further investigation, however, it was perceived that the estimate of the frequency was entirely wrong on account of failure to take into consideration the resistance of the spark gap itself. When the length of this was reduced so that its resistance became inconsiderable and the discharge current actually approached the estimated frequency of 3,000,000, the oscillograph ceased to respond, except by having its elements burned out without deflection. When tested at somewhat lower frequencies its working limit, so far as response to the oscillations was concerned, lay somewhere above 80,000, at which point it became impossible to obtain a record on the photographic film—the limit being fixed by the sensitiveness of the latter to a rapidly moving spot of light of the intensity available. Since the summation of a high-frequency oscillating wave should be nearly zero, I cannot see why we should expect the oscillograph to act otherwise.

Professor Thomson has cited a number of very interesting points that have led him towards the unidirectional theory of discharge, and to these I can add one which seems to somewhat oppose Mr. Creighton's suggestion that oscillations could occur

more readily in the part of the discharge from clouds to earth, than in the ramified discharges among the clouds. If a high-resistance telephone receiver is connected directly between a wireless aerial and the earth, without other inductance or capacity, it will be found that discharges between the clouds produce a rough crackling sound, while a discharge from clouds to earth produces a sharp clicking or series of clicks at intervals suggestive of the "related" discharges of Professor B. Walter, and which correspond, so far as can be distinguished by eye, to the pulsations in the discharge itself. Actually all these latter discharges, that is, the sharp clicks, are preceded by more or less prolonged noises of the former variety, which, I imagine, indicate the breaking down of the air in the body of clouds—in fact, the "progressive breakdown" described by Dr. Steinmetz. For the same reason I ascribe the sharp clicks to the disruption of the atmosphere between earth and clouds, the sounds of which certainly do not suggest the existence of high or even moderate frequencies.

I think almost all of us have become so attached to the high-frequency theory of lightning discharges that it is very difficult to conceive of anything else occurring. Perhaps, also, some of the discharges in the laboratory which we have heretofore considered high frequency are after all only unidirectional discharges of exceedingly steep wave-front. After all, there is very little difference between the two, since the rapid rise of current from zero to maximum in the latter type of discharge is practically equivalent to the first quarter period of an oscillation, if its frequency is sufficiently high. Over and beyond this, the effects produced by the two will be practically identical except where resonance conditions are involved.

Presented at the 294th meeting of the American Institute of Electrical Engineers, Washington, D.C., April 24, 1914, under the auspices of the Electrophysics Committee.

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SOME SIMPLE EXAMPLES OF TRANSMISSION LINE SURGES

BY W. S. FRANKLIN

ABSTRACT OF PAPER

The paper treats of the true wave phenomena which take place on a transmission line when switches are opened and closed or when a circuit breaker operates. These phenomena are practically the same in alternating- and direct-current systems for transmission lines up to say 150 or 200 mi. (240 or 320 km.) in length, and therefore the surges which are described in the paper are the surges which take place when a steady voltage is connected to the line or when the line is disconnected with a steady current flowing in it.

The details of line surging which takes place under such conditions are most easily described in terms of what may be called the " ribbon wave ", and the first part of the paper is devoted to a discussion of the ribbon wave. Then a number of practical examples are described in detail.

THE LINE surges which are described in this paper are so rapid on transmission lines of moderate length that all the details as described take place during a very small fraction of a second and any change of 60-cycle voltage or current is negligible during the very short interval of time involved. Therefore the effects which are described occur in substantially the same way in direct-current systems and in alternating-current systems.

The effects of line resistance and leakage on a line surge are extremely complicated; indeed, these effects cannot be expressed in finite algebraic terms. Usually, however, line resistance and leakage are small, and therefore a line surge on an actual transmission line approximates in its early stages the character it would have if line resistance and leakage were zero. Line resistance and leakage are assumed to be zero throughout the following discussion.

The complete solution of the differential equation of wave motion on a transmission line is involved in or expressed by the simple idea of travel[1]; and the use of this idea is exactly equiva-

1. This is by no means the case when line losses are taken into account.

lent to the use of the general analytical solution of the differential equation of wave motion; namely:

$$y = f(x - vt) + F(x + vt) \qquad (1)$$

To solve a particular problem, the two unknown functions f and F must be determined so as to satisfy the given conditions which exist over the line at the beginning ($t = 0$), and so as to satisfy the conditions which are continuously impressed on the

FIG. 1

line at its ends. In this connection it must be remembered that either of the functions f or F may be zero or a constant, and it must also be remembered that any number of separate solutions of the differential equation of wave motion can be superposed upon each other to get a desired solution. Thus the heavy dotted line AB in Fig. 17 represents a constant initial distribution of current over the transmission line; and when the end of the line in Fig. 17 is opened, a long-drawn-out wave shoots out from the

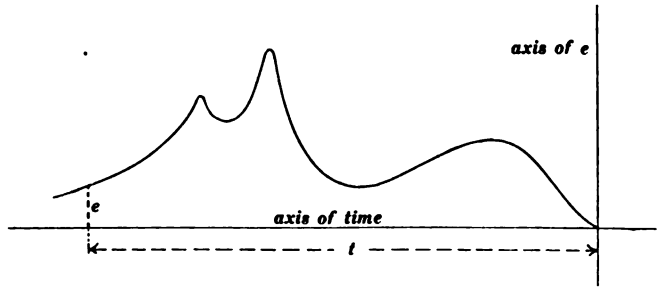

FIG. 2—SHOWING VOLTAGE e OF FIG. 1 AS A FUNCTION OF THE TIME

opened end, and is repeatedly reflected at A and B. The superposition of the initial current and any number of successive laps of the long-drawn-out wave gives the desired solution of the differential equation of wave motion.

An interesting example is to consider the effect produced when a variable voltage e is applied to one end of an indefinitely long transmission line as shown in Fig. 1. The curve in Fig. 2 expresses e as a known function of the time, and the wave that shoots out from e in Fig, 1 is shown by the curve in Fig. 3. The

curve in Fig. 3 evidently gives the correct solution, because in the first place the idea of travel satisfies equation (1), that is to say, the idea of travel satisfies the differential equation of wave motion; and in the second place the value of e in Fig. 3 is equal to the value of e in Fig. 2 at all times, that is to say, the wave in

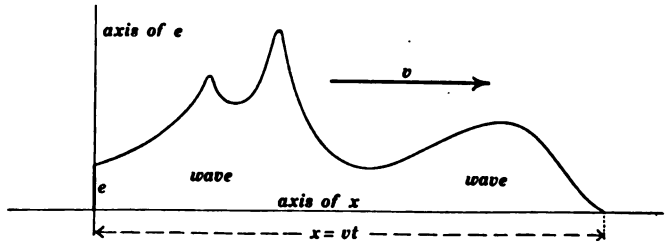

FIG. 3—SHOWING SHAPE OF WAVE WHICH SHOOTS OUT FROM e IN FIG. 1

Fig. 3 satisfies the condition which is continuously impressed upon the line at the end e in Fig. 1.

A clear idea of the essential details of an electromagnetic wave on a transmission line may be obtained with the help of Fig. 4. The curve W W in the lower part of the figure represents the shape of the wave, that is to say, the ordinate y represents the current

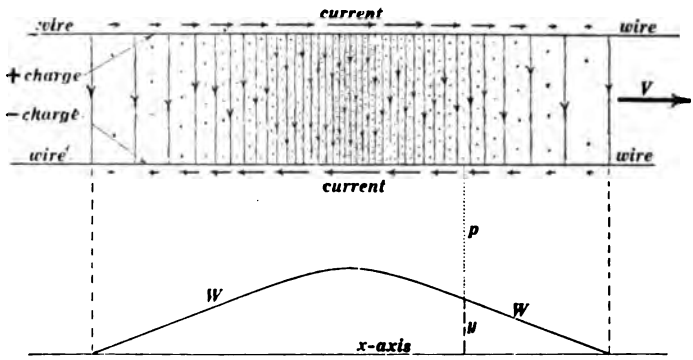

FIG. 4—SHOWING AN ELECTROMAGNETIC WAVE ON A TRANSMISSION LINE

in the wires at the point p or the voltage between the wires at the point p, and of course the curve W W may be of any shape whatever. The dots in Fig. 4 represent the magnetic lines of force which are perpendicular to the plane of the paper.

1. *Relation between Current and Voltage in a Pure Wave.* The differential equation of wave motion on a transmission line

(when line losses are negligible) involves a fixed relation between voltage and current on a line in connection with a traveling wave.

This relation is

$$\frac{E}{I} = \pm\sqrt{\frac{l}{c}} \tag{2}$$

where l is the inductance of the line per mile, and c is the capacity of the line per mile. Hereafter the letter a will be used for $\sqrt{\frac{l}{c}}$. By proper choice of algebraic signs the relation between E and I becomes

$$\frac{E}{I} = +a \tag{3}$$

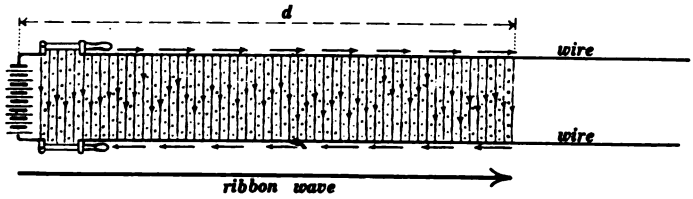

FIG. 5—SHOWING THE RIBBON WAVE WHICH SHOOTS OUT FROM A BATTERY WHICH IS SUDDENLY CONNECTED TO THE END OF THE LINE

The voltage between the line wires within the wave is everywhere equal to battery voltage E, and the current in each wire within the wave is equal to E/a.

for a wave which is traveling to the right, and

$$\frac{E}{I} = -a \tag{4}$$

for a wave which is traveling to the left.

2. *The Ribbon Wave.* Fig. 5 represents an indefinitely long transmission line to which a battery has been suddenly connected. Assuming battery resistance to be negligible, the result is that battery voltage E and the corresponding current I ($= E/a$) is established in the line by a long-drawn-out wave which shoots out from the battery. This is a simple example of the general case which is shown in Figs. 2 and 3. If the distance d in Fig. 5 is 18.6 mi. (29.93 km.), then Fig. 5 represents the state of affairs 0.0001 of a second after the closing of the switch. The long-

drawn-out wave in Fig. 5 may be completely represented by the heavy arrow at the bottom of the figure, if it be remembered that the arrow represents the existence of a certain voltage E and the corresponding current I at each point along the line. In most of what follows we have to do with what are called *rectangular waves*. A rectangular wave is a wave in which the voltage has everywhere the same value E, and in which the current has everywhere the same value I.

3. *Reflection of a Rectangular Wave from the Open End of a Line.* The doubled arrow in Fig. 6 represents a wave which has been partly reflected at the open end of a transmission line. The voltage and current in the original wave are E and I, and the voltage and current in the reflected wave are E_r and I_r respectively. No energy can be delivered to the end of the line, therefore voltage and current have the same values in the reflected wave as in the original wave. The direction of progression of the reflected wave being the reverse of that of the original wave requires that either voltage or current be reversed, but not both. The total voltage at the end of the line $E+E_r$ can have any value whatever, but the total current $I+I_r$ must be zero. Therefore $I_r=-I$ and $E_r=E$. *Reflection takes place with reversal of current at the open end of a transmission line.*

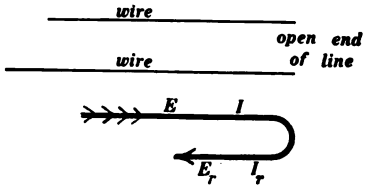

FIG. 6—SHOWING A WAVE PARTLY REFLECTED FROM THE OPENED END OF A LINE

4. *Doubling of Voltage by Reflection.* When reflection takes place with reversal of current and without reversal of voltage, it is evident that an excessive voltage is produced in the region where the reflected wave and the original wave overlap. Thus the reflection in Fig. 6 is with reversal of current so that $E_r = E$, and therefore the voltage is $2E$ in the region where the reflected wave and the original wave overlap.

A wave is reflected from an inductive receiving circuit so that $E_r = E$ at the beginning of the reflection, as explained in connection with Fig. 9. Therefore a doubled voltage is produced in this case.

This rise of voltage due to reflection is important. Thus a wave may enter an underground cable with insufficient voltage to damage the cable, but if the other end of the cable is open, or if inductive apparatus is connected across the other end of the cable, then a doubled voltage will be produced when the wave

is reflected from the other end of the cable. If such a cable must not be subjected to more than 2000 volts, a spark-gap arrester breaking down at 1000 volts must protect the cable where it connects to an air line.

5. *Reflection of a Rectangular Wave from the Closed End of a Line.* The double arrow in Fig. 7 represents a wave which has been partly reflected from the short-circuited end of a transmission line. No energy can be delivered to the end of the line, therefore voltage and current have the same values in the reflected wave as in the original wave. The direction of progression of the reflected wave is opposite to the direction of progression of the original wave; therefore either voltage or current must be reversed, but not both. The total current at the end of the line $I + I_r$ can have any value whatever, but the total voltage $E + E_r$ must be zero.

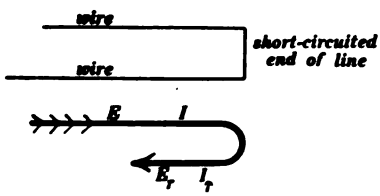

FIG. 7—SHOWING A WAVE PARTLY REFLECTED FROM THE SHORT-CIRCUITED END OF A LINE

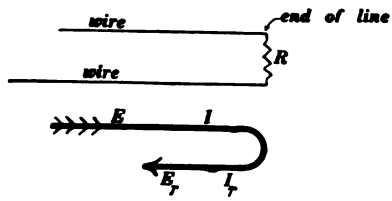

FIG. 8—SHOWING A WAVE PARTLY REFLECTED FROM A NON-INDUCTIVE RECEIVING CIRCUIT OF RESISTANCE R

Therefore $E_r = -E$ and $I_r = I$.

Reflection takes place with reversal of voltage at the closed end of a transmission line.

6. *Reflection of a Rectangular Wave from a Non-Inductive Circuit connected across the End of a Line.* The doubled arrow in Fig. 8 represents a wave partly reflected from a non-inductive circuit of which the resistance is R. The ratio of voltage to current must be the same in the original and in the reflected wave, except for reversal of sign, therefore

$$\frac{E}{I} = +a \tag{5}$$

and

$$\frac{E_r}{I_r} = -a \tag{6}$$

These two equations define the original wave and the reflected wave as pure waves, the only kind which can exist if line resistance and line leakage are negligible. The total current at the end of the line in Fig. 8 is $I + I_r$, and this current flows through the receiving circuit. The total voltage across the end of the line in Fig. 8 is $E + E_r$, and this voltage acts across the receiving circuit. Therefore, since the receiving circuit is non-inductive we have

$$I + I_r = \frac{E + E_r}{R} \tag{7}$$

The original wave is supposed to be given, and the ratio E/I necessarily satisfies equation (5). Equations (6) and (7) contain, therefore, the two unknown quantities, E_r and I_r, and solving for these quantities we get

$$E_r = E\left(\frac{R - a}{R + a}\right) \tag{8}$$

and

$$I_r = I\left(\frac{a - R}{a + R}\right) \tag{9}$$

When $R = a$ and there is no reflected wave at all, the entire original wave is swallowed up, as it were, by the receiving circuit.

When R is greater than a, there is partial reflection with reversal of current; thus when $R = 3\,a$, we get $E_r = \frac{1}{2}\,E$, and $I_r = -\frac{1}{2}\,I$.

When R is less than a, there is partial reflection with reversal of voltage; thus when $R = \frac{1}{3}\,a$, we get $E_r = -\frac{1}{2}\,E$, and $I_r = \frac{1}{2}\,I$.

7. *Reflection of a Ribbon Wave from an Inductive Receiving Circuit.*[2] The solution of this problem is completely represented in Fig. 9 for the case in which $R = \frac{1}{3}\,a$. At the instant that the head of the ribbon wave strikes the receiving circuit the reflection is complete with reversal of current ($E_r = E$ and $I_r = -I$), because an appreciable current cannot be instantaneously established in the inductive receiving circuit. Current is, however, slowly established in the receiving circuit, and the reflected wave becomes weaker and weaker, passes through zero, and then grows stronger and stronger again, until finally we get that particular degree of steady reflection with reversal of voltage ($E_r = -\frac{1}{2}\,E$,

2. The analytical solution of this problem is given in Franklin's "Electric Waves," pages 99–101.

and $I_r = \frac{1}{2} I$) which depends upon R alone. The curves cc in Fig. 9 are exponential curves, and the value of the exponent is $-\frac{R+a}{L} \cdot t$, where t is the abscissa expressed in seconds.

8. *Transmission Line Surges which Follow the Switching on of a Generator.* A generator of negligible resistance and reactance is suddenly switched on to a line, and a ribbon wave of generator

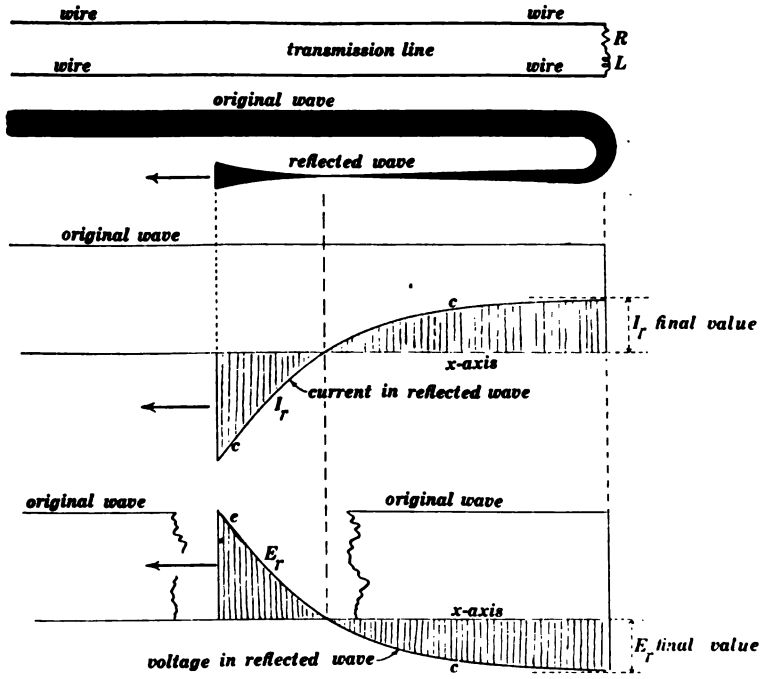

FIG. 9—SHOWING REFLECTION OF A RIBBON WAVE FROM A RECEIVING CIRCUIT OF RESISTANCE R AND INDUCTANCE L, WHEN $R = \frac{1}{3} a$

voltage and corresponding current $\left(\frac{E}{I} = a\right)$ shoots out along the line. Assuming line resistance and leakage to be negligible, this ribbon wave is reflected back and forth as indicated in Fig. 10 or Fig. 11, and by adding together the voltages and currents in the successive laps, a precise knowledge of the distribution of current and voltage over the line at any instant may be obtained. Thus, after a thousandth of a second, the total travel would be 186 mi. (300 km.), and by dividing this travel by the length of the line we get the number of laps of the ribbon wave, with a certain

fraction of the next lap. By carefully reckoning up successive laps in this way complete curves can be easily plotted, showing the voltage across the line and the current in the line at any point of the line as functions of elapsed times. The ampere-time curves in Figs. 10 and 11 were obtained in this way.

The ribbon wave is reflected from the distant end of the line with reversal of current or voltage according as the distant end of the line is open or closed; and the character of the reflection of the ribbon wave at the battery end of the line is determined by

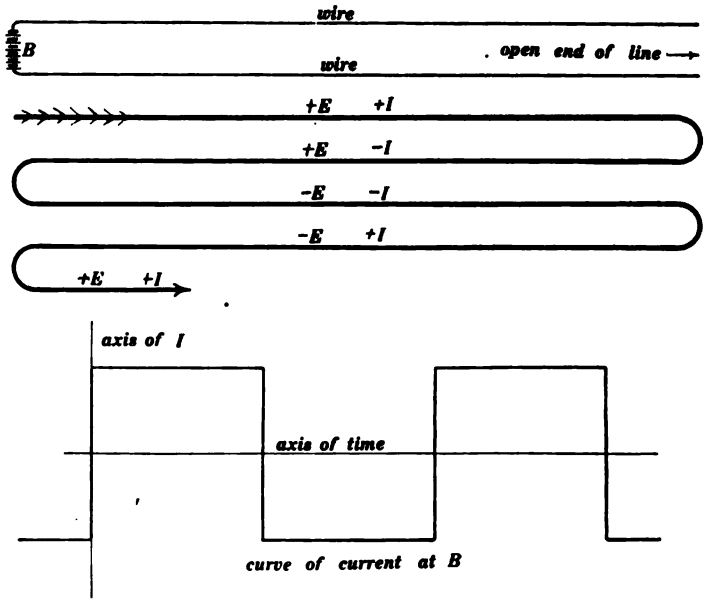

FIG. 10—SHOWING WAVE WHICH SHOOTS OUT FROM A SUDDENLY CONNECTED BATTERY, WAVE BEING REPEATEDLY REFLECTED AT BOTH ENDS OF THE LINE

the condition that the total voltage across the battery end of the line must always be equal to battery voltage.

Fig. 12 shows what happens when a generator of negligible resistance and inductance is switched on to a transmission line, a non-inductive receiving circuit being connected across the other end of the line. Fig. 12 shows the case in which $R = 3a$. In this case voltage and current are each reduced to half, and current is reversed by reflection from R. The character of the reflection from the battery end B is determined by the same condition as in

Figs. 10 and 11, and this reflection is complete, battery resistance being negligible.

Fig. 13 shows the growth of current at B in Fig. 12 and Fig. 14 shows the growth of current at R in Fig. 12 for the case in which $R = \frac{1}{3}a$. In this case voltage and current are each reduced to half, and voltage is reversed by reflection from R.

9. *Reflection at a Place where the Line Constants Change.* An

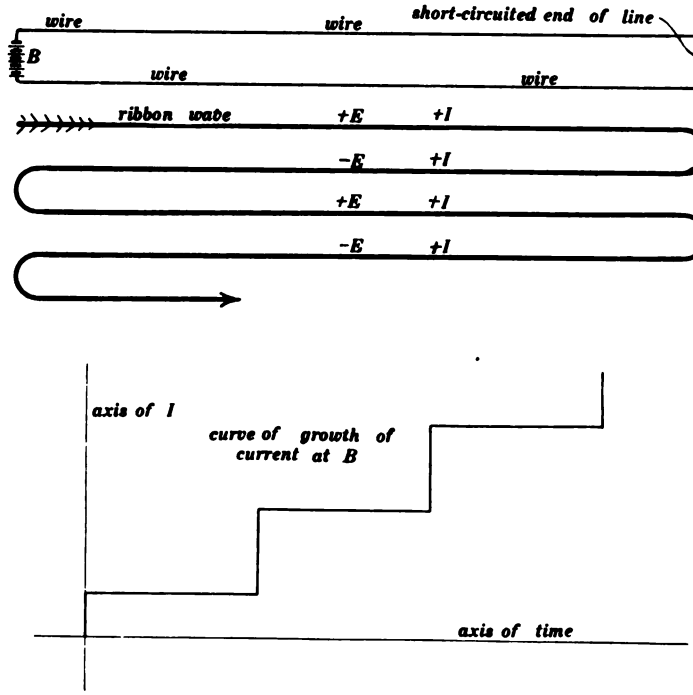

FIG. 11—SAME AS FIG. 10 EXCEPT THAT THE DISTANT END OF THE LINE IS SHORT-CIRCUITED

important case to consider is where an air line connects with an underground cable as shown in Fig. 15. A rectangular wave with voltage E and current I is partly turned back or reflected from the end of the cable, and partly transmitted into the cable. It is required to find the voltage and current values E_r and I_r in the reflected wave, and the voltage and current values E_t and I_t in the transmitted wave.

There are two expressions for the total voltage across the line

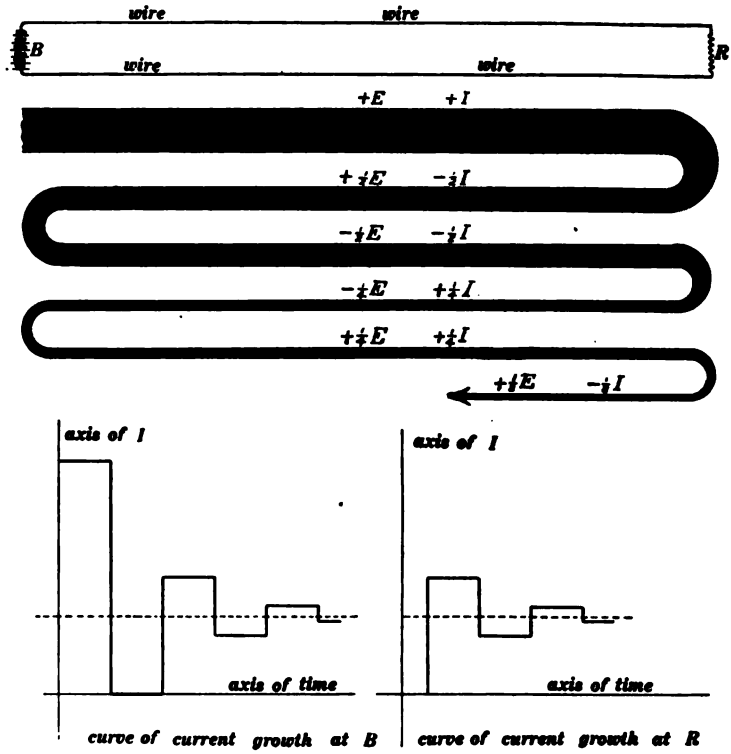

FIG. 12—SHOWING A RIBBON WAVE PARTIALLY REFLECTED AT R ($= 3a$) AND COMPLETELY REFLECTED AT B

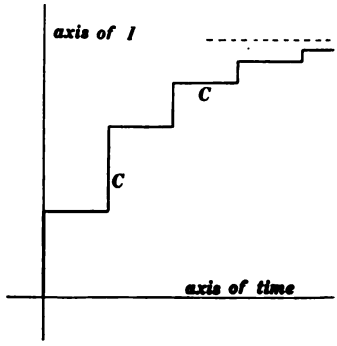

FIG. 13—SHOWING GROWTH OF CURRENT AT B IN FIG. 12, WHEN $R = \frac{1}{3}a$

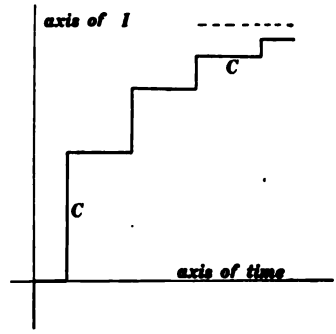

FIG. 14—SHOWING GROWTH OF CURRENT AT R IN FIG. 12, WHEN $R = \frac{1}{3}a$

at p, namely, $E + E_r$ on the one hand, and E_t on the other hand, and these two expressions must be equal. Therefore

$$E + E_r = E_t \tag{10}$$

Also, the total current $I + I_r$ must be equal to I_t, so that we have

$$I + I_r = I_t \tag{11}$$

Furthermore, we have

$$\frac{E}{I} = +a \tag{12}$$

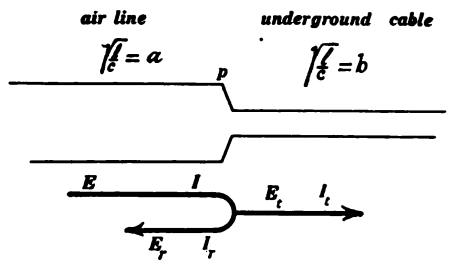

FIG. 15—SHOWING WAVE PARTLY REFLECTED AT A POINT WHERE AN AIR LINE CONNECTS WITH AN UNDERGROUND CABLE

$$\frac{E_r}{E_r} = -a \tag{13}$$

and

$$\frac{E_t}{I_t} = +b \tag{14}$$

From these equations we find

$$E_r = \frac{b-a}{b+a} \cdot E \qquad E_t = \frac{2b}{a+b} \cdot E$$

$$I_r = \frac{a-b}{a+b} \cdot I \qquad I_t = \frac{2a}{a+b} \cdot I$$

For example, a wave in which $E = 1412$ volts and $I = 2$ amperes ($a = 706$ ohms) travels along an air line, and comes to

the end of a cable for which $b = 100$ ohms. Under these conditions $E_r = -1063$ volts, $I_r = +1.5$ amperes, $E_t = +349$ volts, and $I_t = +3.5$ amperes.

10. *Reflection at a Place where a Line Branches.* Fig.16 represents a place where a line branches into two similar lines. The doubled arrow represents a partly reflected rectangular wave, and the two transmitted waves are exactly alike because the branch lines are similar. Equating voltages across branch point, we have

$$E + E_r = E_t \tag{15}$$

Equating currents on two sides of branch point, we have

$$I + I_r = 2\,I_t \tag{16}$$

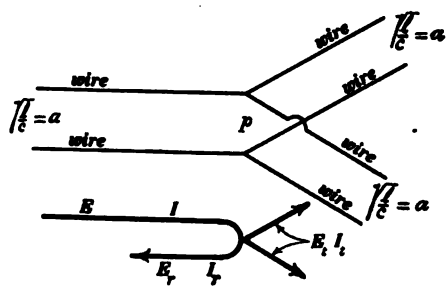

FIG. 16—SHOWING WAVE PARTLY REFLECTED AT A BRANCH POINT OF AN AIR LINE

Also, for each individual wave we have

$$\frac{E}{I} = +a \tag{17}$$

$$\frac{E_r}{I_r} = -a \tag{18}$$

$$\frac{E_t}{I_t} = +a \tag{19}$$

and from these equations we find

$$E_r = -\tfrac{1}{3}\,E \text{ and } I_r = +\tfrac{1}{3}\,I$$

and

$$E_t = \tfrac{2}{3}\,E \text{ and } I_t = \tfrac{2}{3}\,I$$

That is, the reflected wave represents 1/9 of the energy of the original wave, and each transmitted wave represents 4/9 of the energy of the original wave.

11. *Transmission Line Surges which are Produced when a Circuit Breaker Opens.* When a circuit breaker opens, the arc which is formed persists for a very long time, relatively speaking, and the open gap in the circuit is filled with a fairly good conducting material which slowly loses its conductivity. It is about as nearly impossible to produce characteristic line surges by opening a circuit breaker as it would be to set up an abrupt water wave in a canal by allowing a cubic mile of soft mud to flow into the canal prism to stop a troublesome flow of water in the canal; and yet the moon, as a 60-cycle generator (60 cycles per month!)

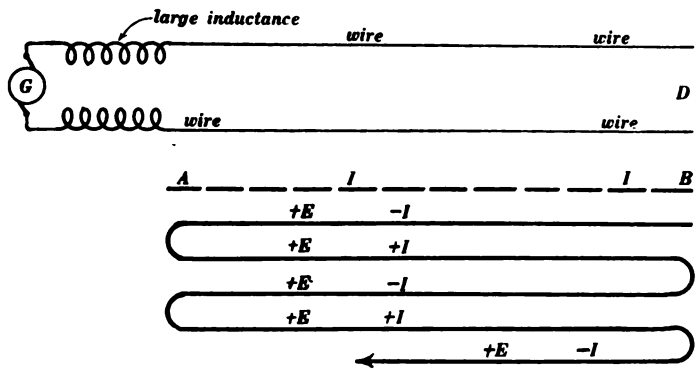

FIG. 17

The dotted line AB represents the initial current in the transmission line. The long heavy arrow represents the ribbon wave which comes from D after the line at D is opened.

might produce a troublesome tidal wash in a large estuary while the attempt was being made to " open-circuit " the estuary in this Brobdingnagian fashion! Let the reader consider this hydraulic analog carefully. It produces nearly all of the essentials of the electrical case. The conducting vapor in the arc of a circuit breaker is somewhat analogous to mud as a dam-building material.

Very little need be said of characteristic line surges in connection with opening of switches, except in the case of very long lines. When a line is short, or only moderately long, what takes place may be described quite accurately in terms of the simple ideas of elementary alternating-current theory, where current values are supposed to rise and fall simultaneously throughout an entire

circuit. The formation of a long arc between line wires in air, and the quick snapping out of such an arc, is the only case known to the writer where an electric wave disturbance can be produced by opening the circuit of a transmission line of moderate length, and the essential features of this case are shown in Fig. 17. Imagine the system to be short-circuited by an arc at the distant end D of the transmission line, voltage being reduced to a negligibly small value over the whole line, and a large current I established in the line. The generator is to be thought of as having a large inductance so that the generator current cannot change perceptibly during the very short time required for the characteristic line surges. When the distant end of the line is opened, a ribbon wave shoots towards the generator, is completely reflected at the generator with reversal of current, again completely reflected at the opened end D of the line with reversal of current, and so on. The first lap of this ribbon wave wipes out the current in the line and lays down a certain voltage E ($= aI$). The second lap of the ribbon wave lays down a double voltage, and the original current. The third lap wipes out the current again, and lays down a voltage equal to $3\,E$, and so on.

It must not be imagined that the sending out of a ribbon wave depends upon a continued supply of energy at the point where the ribbon wave originates. Thus in Fig. 17 the ribbon wave is superposed upon the initial current I, and the first lap of the ribbon wave wipes out this current. Therefore, since the current is zero, there is no energy flow at all from the opened end. The second lap of the ribbon wave lays down the original current I and a doubled voltage $2E$ ($= 2\,aI$), and this combination of voltages and current represents the flow of energy from the generator into the line.

DISCUSSION ON "SOME SIMPLE EXAMPLES OF TRANSMISSION LINE SURGES" (FRANKLIN), WASHINGTON, D. C., APRIL 24, 1914.

J. Murray Weed: The steepest wave fronts which are produced in the practical operation of electrical systems are those caused by the sudden making or breaking of a circuit. A discharge to ground would come under this classification, although this may not constitute the making of a circuit which it is desired to make. It does not seem likely, however, that the making of a circuit which takes place by the rupturing of air, oil, or some other dielectric, would result in the rectangular waves which are presented in Dr. Franklin's paper. When we consider the velocity of 186,000 miles a second, it becomes obvious that a phenomenon which is instantaneous, so far as our ability to measure time is concerned, may distribute its effects over a very considerable length of a transmission line. Furthermore, it is my belief that if, by any means, a perfectly abrupt or sheer wave front were produced in a transmission line, it would be very rapidly decomposed, and that at a considerable distance from the point of its formation it would have become considerably tapered.

We do have good evidence, however, that wave fronts may be produced which are so steep as to be dangerous to the turn-to-turn insulation of inductive apparatus; sometimes so steep, in fact, as to rupture insulation which has been specifically designed to withstand this sort of disturbance. Moreover, there is no doubt that most of the voltage disturbances in transmission lines originate as traveling waves, or impulses. The method of treatment used by Dr. Franklin is very useful in investigating the behavior of such disturbances and also in investigating various methods of protecting from these disturbances. They have been used already to good advantage by several German writers, notably K. W. Wagner. I myself have been making a study of this nature, some of the more important results of which I hope to publish in the near future.

The written discussion which I have submitted gives a treatment somewhat parallel to Dr. Franklin's, in which I have undertaken to make the subject of how and why waves travel, clear to one who has not given the subject any study, but who has, to begin with, merely a fundamental knowledge of inductance, capacity and resistance. It may be, also, that a concise statement of this matter will be of interest to those who are more familiar with the subject.

J. Murray Weed (by letter): If we consider a generator, of zero impedance and of voltage E, connected instantaneously to a pure inductance, the result is a gradual growth of current, such that

$$L \frac{di}{dt} = E \tag{1}$$

The current which enters the inductance at one end is leaving it at the other end at the same instant, since there is no capacity within the inductance for storing up current. The value of L involved in equation (1), therefore, is the total inductance, and since there is no resistance, the growth of current is uniform and continuous.

If the same generator be suddenly connected to the end of one wire of an indefinitely long transmission line of zero losses by closing the switch, our conception of the method in which the line would be charged is as follows:

The capacity of the first element of the line is instantly charged. But current must flow through the inductance of this element to charge the second element, and this requires an instant of time. After the second element is charged there is no further growth of current in the first element, since there is no difference of potential applied to this element. The current set up at the first instant merely continues to flow, supplying the necessary charging current for successive elements of the line, and current grows in but one element at a time, this growth being by an instantaneous change from $i = 0$ to $i = I$. The current I and the electrostatic charging of the line to voltage E advance together with a sheer wave front, so that the total voltage of the circuit appears at the front of the wave. We find the relation between this action and the growth of current in the pure inductance of the first case, as follows:

Equation (1) may be written in the form

$$d\frac{(Li)}{dt} = E \tag{2}$$

and for the transmission line, since we assume an instantaneous growth of current from zero to a constant maximum value in successive elements of inductance, we may say that we have constant current, with gradual increase of inductance, so that equation (2) becomes

$$I\frac{dL}{dt} = E \tag{3}$$

If L_0 = the inductance per unit length of the line, this becomes

$$I L_0 \frac{dy}{dt} = E$$

or

$$I L_0 dy = E dt \tag{4}$$

where y = distance along the line.

If Y = the total length of the line, and T = the time required for the charging wave to traverse the line, the integration of equation (4) gives

$$I Y L_0 = E T \tag{5}$$

Considering now the relation between current, voltage, and the capacity of the line, we find similarly the equation

$$E\,C_0\,dy = I\,dt \tag{6}$$

where C_0 is the capacity per unit length of the line. The integration of this equation gives

$$E\,Y\,C_0 = I\,T \tag{7}$$

From equations (5) and (7) we obtain directly the time required for the charging wave to traverse the line,

$$T = Y\,\sqrt{L_0\,C_0} \tag{8}$$

and since the velocity equals the length of the line divided by the time, we have

$$v = \frac{1}{\sqrt{L_0\,C_0}} \tag{9}$$

From (5) and (7) we also obtain

$$\frac{L_0\,I^2}{2} = \frac{C_0\,E^2}{2} \tag{10}$$

Since the first member of this equation represents the electromagnetic energy per unit length, and the second member the electrostatic energy per unit length, equation (11) shows the equality between the electrostatic energy and the electromagnetic energy of the advancing wave, which is a characteristic of all pure traveling waves. The total energy per unit length of the charging wave thus is

$$W = \frac{L_0\,I^2}{2} + \frac{C_0 E^2}{2} = L_0\,I^2 = C_0\,E^2 \tag{11}$$

This energy per unit length multiplied by the velocity of the wave gives the power absorbed from the generator. Thus, from equations (9) and (11),

$$P = L_0\,I^2\,\frac{1}{\sqrt{L_0\,C_0}} = I^2\sqrt{\frac{L_0}{C_0}} \tag{12}$$

and

$$P = C_0\,E^2\,\frac{1}{\sqrt{L_0\,C_0}} = \frac{E^2}{\sqrt{\frac{L_0}{C_0}}} \tag{13}$$

So far as the generator is concerned, with an indefinitely long transmission line, this power is lost, just as much as though it had been consumed by the resistance

$$R_0 = \sqrt{\frac{L_0}{C_0}} \tag{14}$$

The quantity $\sqrt{\frac{L_0}{C_0}}$ is, in fact, measured in ohms, and may be called the wave resistance of the line.

From the equation (11) or directly from equations (5) and (7), we have also

$$I = \frac{E}{\sqrt{\frac{L_0}{C_0}}} = \frac{E}{R_0} \tag{15}$$

Thus Ohm's law may be applied to a transmission line with respect to traveling waves, and shows how much current will flow into the line with a given voltage applied. This must be restricted, of course, to the initial period of charging the line.

If we examine a point in the line after the wave front has passed, we find the constant current I flowing at the constant voltage E, which is the generator voltage, supplying the power

$$P = E\,I = I^2 R_0 = \frac{E^2}{R_0} \tag{16}$$

These values of P are the same as that given by equation (13).

Now, if the generator voltage is suddenly reduced to zero, current ceases to enter the line from the generator. One might, at first thought, expect the current to begin to flow back from the line into the generator. This, however, is not the case. The wave of current and voltage continues to progress in the line. The rear end of the wave is similar to the front end, except that the voltage E existing in the line, here acts in a direction toward the generator, instead of away from the generator, and we have here a counter e. m. f. which is away from the generator, due to the cessation of current in that inductance from which the rear end of the wave is passing, whereas the counter e. m. f. at the front of the wave is toward the generator, due to the current entering the inductance which is in advance of the wave. Kirchoff's law for voltage is satisfied at both ends of the wave, as expressed for the front end by equation (4). The same equation may be used for the rear end, but the opposing e. m. f's are reversed with respect to the positive direction in the circuit. If we change signs on both sides of the equation to account for this, we have

$$-I\,L_0\,dy = -E\,dt \tag{17}$$

This equation for the rear end of the wave may be looked upon as belonging to a wave front of opposite polarity, the front of a wave of negative current and negative voltage, superposed upon the former wave of positive current and positive voltage, and thus reducing both current and voltage to zero.

The above deductions were made with respect to an abrupt or sheer wave front. If a practical generator, or generator and step-up transformer, of large inductance, be suddenly connected to the end of a line, the charging wave will not be abrupt, since the current I must grow in the inductance of the generator. The growth of current and voltage at the entrance of the transmission line are logarithmic, as expressed by the equations

$$i = \frac{E}{R_0}\left(1 - e^{-\frac{R_0}{L}t}\right) \tag{18}$$

and

$$e = E\left(1 - e^{-\frac{R_0}{L}t}\right) \tag{19}$$

where $R_0 = \sqrt{\frac{L_0}{C_0}}$ is the wave resistance of the line, as found above for the abrupt wave, L is the inductance of the generator and t is the time measured from the instant of closing the switch. Substituting the value

$$t = y\sqrt{L_0 C_0} \tag{20}$$

these equations become

$$i = \frac{E}{R_0}\left(1 - e^{-\frac{L_0}{L}y}\right) \tag{21}$$

and

$$e = E\left(1 - e^{-\frac{L_0}{L}y}\right) \tag{22}$$

which give the current and voltage at a point in the wave distant y from the tip of the wave which entered the line at the first instant.

That such a tapered wave, or in fact a wave of any shape, will follow the same laws as the wave with abrupt front and rear, is easily inferred by thinking of the tapered wave as made up of infinitesimal abrupt waves, distributed in time, or in space. Equations (4) and (6) can be applied to each of these differential waves and integrated with respect to distance and time, giving in lieu of equations (5) and (7),

$$di\, Y L_0 = de\, T \tag{23}$$

and

$$de\, Y C_0 = di\, T \tag{24}$$

All of these differential waves, therefore, follow the same laws of propagation, reflection and refraction as a finite abrupt wave.

Thus, the velocity of each element of the wave will be the same, and the same proportions are reflected, and refracted. The wave shape of the tapered or irregular wave, obtained by the superposition of all of the differential elements, is therefore preserved, and the same proportionality will exist between the original wave and its reflections and refractions as with the abrupt wave; although this statement would have to be modified where the reflecting agent is reactive.

Some consideration of the nature of so-called reflections of the traveling wave will make this subject clearer to those who are not already familiar with it. Thus, for instance, at the instant when the abrupt wave reaches the end of the line, we find the entire line charged to voltage E, and the current I flowing throughout its length. The condition at this instant is the same, whether the line be open or closed. If the line is open, since the current can not flow out at the end of the line, it supplies additional charge to the end of the line, and so builds up the voltage to a higher value than E. The question as to how high this voltage will build has been answered by saying that the wave is completely reflected, with negative current and positive voltage, this reflected wave superposed upon the oncoming wave giving zero current and double voltage.

This statement, however, does not give the true fact, but a fictitious condition which is equivalent to the fact. The fact is that the line retains its charge corresponding to the voltage E, while the current I acts in the same manner as it would if it had been flowing through the line, with no voltage at all present, and were suddenly interrupted at the end of the line. With the building up of a certain voltage E' in the last element of the line, current must cease in the next to the last element. Otherwise the voltage would continue to build up indefinitely. Voltage will then build up in the next to the last element, with cessation of current in the preceding element, etc. The voltage E^1 is acting in a direction against the current or the negative direction, while an equal counter e. m. f. in the positive direction is produced by the reduction in the amount of inductance occupied by the current I. This balance of e. m. f's is expressed by equation (**4**) with the appropriate changes in signs. Thus

$$I L_0 (- dy) = -E'dt \tag{25}$$

This equation may be looked upon as applying to a wave of negative voltage and positive current, traveling in the negative direction, and leaving the line charged to the voltage E'. In the case which we are considering, the line was already charged to voltage E, so that the resultant voltage is now $E + E'$.

If we change signs on both sides of equation (**25**), thus transferring it to the other side of the wave front, we have

$$- I' L_0 (- dy) = E' dt \tag{26}$$

This equation applies to the front of the fictitious reflected wave of positive voltage and negative current, which is supposed to be superposed upon the original wave.

The same considerations which gave us the current which will enter a line with voltage E applied (**15**), will now give us the voltage which will be built up in the line by the current I, namely,

$$E' = I R_0 \tag{27}$$

If reference is made to the fictitious reflected current, which is no doubt the more convenient, we must take account of the negative sign, and (**27**) becomes

$$E' = -I' R_0 \tag{28}$$

where I' is negative.

In the case of the closed-ended line, instead of the line retaining its charge corresponding to voltage E, and the current I building up an additional voltage E', which is equal to E, we find that the current I is uninterrupted, while the voltage E is permitted to set up an additional current I', which is equal to I. Equation (**28**) applies here also, but in this case I' is positive and E' negative.

Professor Franklin has spoken of the effects of line losses as usually small. It can be shown that, as ordinarily considered, they have no effect in destroying the abruptness of the wave, but that they reduce the height of the wave front in accordance with the equation

$$E_y = E_1 e^{-\left(\frac{g}{2G_0}+\frac{r}{2R_0}\right)y} \tag{29}$$

where E_y is the voltage at the wave front, E_1 is the voltage with which the wave enters the line, y is the distance that the wave has traveled, g and r are the insulation conductance and the resistance per unit length of line, and G_0 is the reciprocal of R_0, and may be called the wave conductance of the line.

There is, however, another element of loss, and of energy absorption, which exists only in the wave front, and which does destroy its abruptness. The rapidity of this action I have not yet determined. The action referred to is that of skin effect, the current at the extreme front of an abrupt wave being all at the surface, and becoming gradually diffused after the wave front has passed. I have found that the energy subtracted from the wave within the region wherein this diffusion takes place, corresponds to a resistance of 30 ohms.

With a perfectly abrupt wave front this resistance will be effective with respect to the total current at once, and so will decompose the wave front rapidly. As soon as the wave front becomes tapered, the extra wave front resistance will be effective with respect to only a part of the current at a time, and the energy absorbed is thus reduced, as well as distributed over a greater distance, or longer portion of the wave. This process

of reducing the energy absorbed, and distributing it over greater distance, goes on progressively.

A. G. Webster: To allay the doubts of the last speaker, Mr. Weed, who said that it was impossible for the corners to persist, I will say that that is absolutely true in real lines, but Dr. Franklin has the gift of making things very simple by making certain assumptions.

Some of us are familiar with sound. It happens that sound waves are easier to experiment on than electric waves. The theory given by Dr. Franklin, and the theories advanced in the papers by Mr. K. W. Wagner, in which you will find a number of oscillograms, show these things, how you may have corners in a real circuit, though the corners round off, and the theory is exactly the same as the transmission of plain sound waves. You know that organ pipes correspond exactly to the circuit with a certain amount of inductance, and with a certain amount of capacity, which is elasticity of air. Any wave that enters at one end proceeds to the other end, and is reflected back if the end is open. If the pressure is that of the open air there cannot be any difference, and the pressure wave is reflected back. So, if the end is open there can be no current, and the current is reflected back. On the other hand, if the end is closed, there can be no displacement, because air cannot move against a wall, it being a longitudinal wave. If the electrical wave has an open end where there is no current the potential is doubled. Say that a wave runs back and forth in this tube, it is different at the two ends and has to go back and forth four times before it gets to its former condition, and, therefore the wave length will be four times the length of the tube.

Twenty-one years ago I made some experiments on these surges, not on a cable, for I had none, but on a wire some five or six hundred feet long. On the basis of my experiments I announced that I would present a paper at the International Electrical Congress in Chicago, in 1893, spoken of by President Mailloux earlier this evening. I made a few experiments, enough to justify me in sending in the title of the paper, but as it developed, they were not enough to justify the preparation and reading of a paper, so I withdrew it. The apparatus with which to conduct the experiments was made, but on account of mechanical difficulties it was put aside. Since Dr. Whitehead asked me last week if I would speak on this paper, I have put up a wire again, and made further experiments. I may say that all of Mr. Wagner's experiments were made on an artificial line, a very remarkable line made of coils and condensers and representing all sorts of cables and all sorts of lengths, and his conditions, though simpler, are more like reality than Dr. Franklin's, for he allows you to put in a damping term. My own experiments have borne out the same idea. Such a wave, instead of being a ribbon wave, falls off, as was stated by the last speaker. There is a corner on it, but

this corner goes along with the velocity of light, and when it has reached a given point, it has fallen off by a definite fraction. I showed the proof of that in my book some seventeen years ago. The theory was given some twenty-five to thirty years ago by Oliver Heaviside.

This line that I speak of was merely a copper wire strung up, and a charge is put on. The other end of the wire, which has been brought back by a sufficiently remote route, is connected with an electrometer, and about two-millionths of a second after this discharge has been put on the electrometer is disconnected. The thing is done again, moving the micrometer up so as to make it, say, a millionth of a second, but as this line was only three hundred meters long, it took a millionth of a second to traverse it, and you see the instrument is put under very serious demands, and I am free to say it is not sensitive enough to give satisfactory performance on a very short line. I would like to have a line two or three miles long. A battery is put on here—we will say it is positive. You can easily see that the electrometer can give absolutely no negative readings unless there are surges. As a matter of fact we get a certain number of positive readings scattered around, but we get some negative readings, at least half as big as the positive readings. My instrument is not perfect, but it is sensitive, it will measure to one two-millionth of a second, but it will not do the same thing for one ten-millionth of a second. If I had a longer line I could show these things in a better experiment. That is the experiment I tried to do twenty-one years ago—I did not forget it, but put it aside, and last week I got what I may call positive results.

As has been said, in a real line the wave goes to 186,000 miles per second, but few lines are as long as that. These things happen quickly; that they are real no one doubts; that the potential may be doubled and climb up by steps, etc., all those things are a consequence of theory.

In these papers of Dr. Wagner's you will see real oscillograms; the whole thing is very clear. There is a charge put on a resistance, the potential rises immediately, falls a little, goes up again, and comes back, and so on, and this approaches an asymptote, and then the potential goes down, by successive steps. This was not on a real line, it was on an imitation line, but I presume everybody here believes a statement of Prof. Pupin, which he has evolved from his experiments, that such lines do imitate the real lines to great perfection, provided the coils are subdivided finely enough.

A. Hamilton-Ellis (by letter): I do not agree with the author that very little need be said in connection with the opening of switches on short lines.

In a case which occurred some time ago, at the station where the writer is, the switching-off of a bank of three single-phase transformers, connected in delta on the primary, for supply-

ing a 750-kw. synchronous converter, resulted in wrecking the switch and almost wrecking the cell structure. The transformers were only energized at the time, the converter being shut down.

The supply was at 6600 volts, 25 periods, with one phase earthed, the neutral of the generator being insulated. Between the switch and transformers were approximately 90 ft. of three-core, paper-insulated, lead-covered cable of 0.075 sq. in. section. An examination of the switch, or what was left of it, showed the appearance of an arc having been broken, but it was extremely doubtful.

However, doubts were soon put at rest, for, shortly afterwards, one of the transformers, which had the appearance of an arc having taken place inside it, was disconnected and a generator was run directly upon it. The connection between the generator switch and the transformer was made with 7/16 stranded cable, one pole being grounded. On reaching 6600 volts, the generator switch was accidentally opened, with the result that the switch was wrecked, this wrecking taking place across the terminals outside the switch. An examination of the switch contacts failed to show any sign of an arc having taken place, and the transformer was later found to be all right.

Further tests were carried out with an oscillograph, when it was found that the voltage rise was approximately 5½ times normal, when the switch was opened with these transformers on magnetizing current alone.

Perhaps the author will be able to give a reason for the occurrence. Allowing that in the first instance an arc was drawn out and that the condenser effect of the cable was sufficient to quench it suddenly, the cause is not so self-evident in the second case.

However, the point I wish to bring forward is, that even in the case of the shortest of connecting lines between the generator busbars and the apparatus that is connected thereto, there is every possibility of these surges taking place.

Presented at the 294th Meeting of the American Institute of Electrical Engineers, Washington, D.C., April 25, 1914, under the auspices of the Electrophysics Committee.

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A MILLIAMPERE CURRENT TRANSFORMER

BY EDWARD BENNETT

ABSTRACT OF PAPER

(1) It is pointed out that by the use of a current transformer having a primary to secondary current ratio of the order of 1 to 100, oscillograms can be obtained of the charging current of a single high-tension insulator or of a few feet of high-tension transmission line; that is, oscillograms of currents of the order of 0.1 to 0.5 milliampere may be obtained.

(2) The drawings and specification are given for a transformer for this purpose.

(3) The transformer relations are discussed; the methods of determining the transformer constants are outlined, and the performance of transformers constructed in accordance with the specifications is determined.

(4) A series of oscillograms is given to illustrate some of the applications of the transformer, such as to the study of corona, high-tension insulators, and leakage currents in evacuated lamps.

I—INTRODUCTION. PURPOSE OF THE TRANSFORMER

IN AN investigation of the merits of wooden insulator pins and of the causes of pin charring, conducted in 1908 for the Telluride Power Company, the writer had occasion to construct a current transformer which would permit of obtaining oscillograms of the displacement current across a single high-tension insulator. Since then a similar transformer has been used to determine the effect of corona on the wave form of the displacement current between a 10-ft. (3-m.) length of wire and a concentric 14-in. (35.56-cm.) pipe.

The first transformers were designed to have a current ratio of 100, but on test developed a ratio of only 89; moreover, it was evident that high harmonics were getting through the primary winding as a displacement current from layer to layer.

Computations, based on the assumption that the primary was wound in layers, had indicated that the displacement current between layers at 60 cycles would be less than 0.2 per cent of the total current. After the test, these computations were rechecked with the same results as before, and for some time the discrepancy remained inexplicable. The cause of the discrepancy was eventually discovered and eliminated only by a chance observation.

In view of this experience and of the merits of the transformer for certain lines of investigation, a description of the construction and characteristics of the perfected transformer would seem to be warranted and is herewith presented.

Purpose of the Transformer. A deflection of one centimeter on oscillograms from the oscillograph used is obtained with a

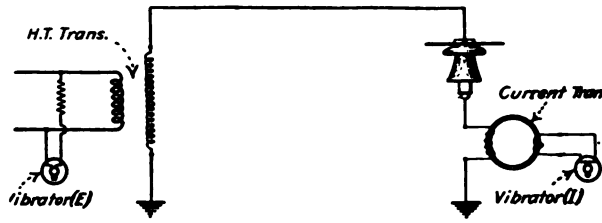


FIG. 1—CONNECTIONS FOR INSULATOR OSCILLOGRAMS

current of from 0.05 to 0.08 peak ampere. Oscillograms with a peak deflection of less than 0.5 cm. are not very satisfactory, therefore the smallest current which will give a satisfactory oscillogram when passed directly through the vibrator of the oscillograph is 0.02 r.m.s. ampere.

The displacement current at the working voltage from the line

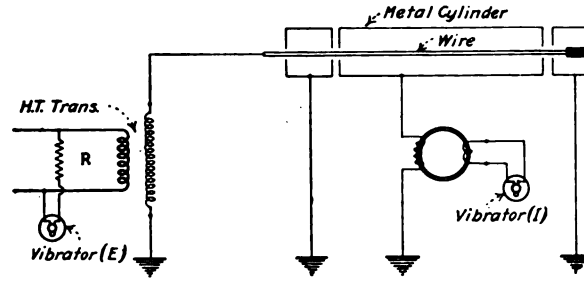
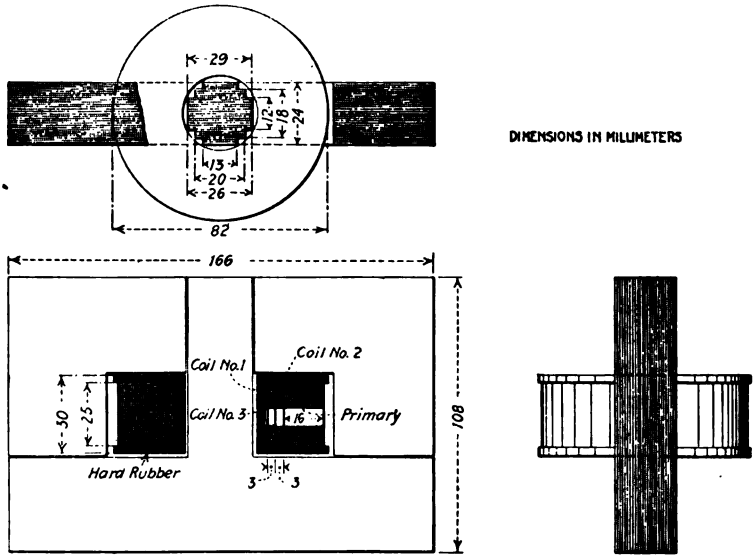


FIG. 2—CONNECTIONS FOR OSCILLOGRAM OF THE CHARGING CURRENT OF A WIRE

wire to the pin of a single high-tension insulator is about 0.0002 ampere at 60 cycles, that is, it is approximately the same as the charging current of six ft. (1.8 m.) of No. 00 B. & S. conductor at 34.6 kv. to ground. Oscillograms of these currents may be obtained by using a current transformer with a current ratio of 100 as shown in Figs. 1 and 2.

II—Description of the Transformer

The construction and dimensions of the transformer are shown in Figs. 3 and 4. Primary and secondary coils are wound on a single hard rubber spool, the secondary coils being at the bottom of the spool. The magnetic circuit comprises a short bridge section within the spool and two wings of greater length but each having 1.8 times the cross-section of the bridge. The laminated core is clamped between two maple blocks on which are mounted the binding posts in which the coils terminate.



Figs. 3 and 4—Milliampere Current Transformer

Specification

Rating.

Secondary current range 0.01 to 0.1 ampere.
Ratios of current transformation 100 and 200.
Primary current range 0.00005 to 0.001 ampere.
Frequency 60 cycles.
Resistance of external circuit 0.6 ohms.
Reactance " " " negligible.

The 200 ratio is for use only in those cases in which very exact phase relations are not essential.

Primary Winding.

16,200 turns of 38 B. & S. gage enameled copper wire.

Mean diameter of turn 6.3 cm.
Total length of wire 3210 meters.
Measured resistance 6650 ohms.

The wire is not wound in single layers but in "sections" of about 600 turns each with a layer of 0.04-mm. tissue paper between sections.

Secondary Winding.

Number of coils 3.
Size of wire No. 20 B. & S. double silk covered copper.
Coil 1 has 1 layer of 27 turns.
  Resistance, 0.11 ohms.
Coil 2 has 81 turns in 3 layers.
  Resistance 0.34 ohms.
Coil 3 has 81 turns in 3 layers.
  Resistance 0.38 ohms.

Coils 2 and 3 are used in series for a ratio of 100 and in parallel for a ratio of 200.

Core.

14-mil (0.36-mm.) silicon steel.
Net section of bridge section 4.2 sq. cm.
Magnetic length of bridge section about 5 cm.
Net section of each wing 7.7 sq. cm.
Magnetic length of wing section 15 cm.
Flux densities at 0.05 ampere secondary:
  36 lines per sq. cm. in bridge.
  10 " " " " " wings.
Joints in the magnetic circuit, 2.

III—Transformer Relations

Fig. 5 is a vector diagram showing the phase relations of currents, voltages, and magnetic flux when the transformer is connected for a ratio of 100 and is delivering 0.05 ampere (effective value) to the secondary circuit. Unless otherwise stated, the following discussion all relates to the 100 to 1 connection of the transformer.

In this diagram,

if $I_2 = 0.05$ ampere represents the current in the secondary then

$E_2 = 0.05\ (r_2 + jx_2)$ represents the voltage that must be induced in the secondary by the magnetic flux.

$E_2 = I_2\ (r_2 + jx_2)$ is the resultant of the two components,

I_2r_2, in phase with the secondary current, and

jI_2x_2, leading the secondary current by 90 deg., where

r_2 is the resistance of the secondary winding plus the resistance of the external circuit supplied by the secondary, and

x_2 is the reactance of the secondary winding due to leakage flux embracing the secondary alone, plus the reactance of the external circuit.

The secondary voltage E_2 is induced by the mutual magnetic flux φ, 90 deg. in advance of and directly proportional to E_2.

To drive the flux φ through the magnetic circuit there is required a magnetizing force consisting of two components, a wattless component M in phase with φ, and a power component W, 90 deg. in advance of φ. The primary current I_1 must furnish this magnetizing force and must in addition neutralize the magnetomotive force of the secondary current I_2.

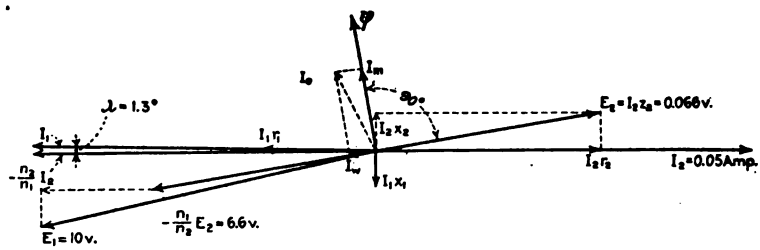


FIG. 5—TRANSFORMER DIAGRAM

NOTE. The exciting current I_e and its components I_m and I_w are drawn to 10 times the scale of the primary and secondary currents.

The primary current then is the resultant of three components:

First, a neutralizing component $I_n = -\frac{n_2}{n_1} I_2$ or in phase opposition to I_2.

Second, a wattless exciting component I_m in phase with φ.

Third, a power exciting component I_w, 90 deg. in advance of φ.

The voltage E_1 consumed in the primary of the transformer is made up of three components:

First, the voltage consumed by the mutual flux φ,

$$= -\frac{n_1}{n_2} E_2.$$

Second, the voltage consumed by resistance in the primary, a voltage in phase with I_1, and equal to $I_1 r_1$.

Third, the voltage consumed by leakage flux linking with the primary alone, a voltage 90 deg. in advance of I_1 and equal to jI_1x_1.

It is seen from this diagram that the reversed secondary current leads the primary current by a small angle, λ, whose tangent is approximately equal to the component of the exciting current in quadrature to the load current divided by the load current. Furthermore, the ratio of the secondary to primary current is less than the ratio of primary to secondary turns, due to the component of the exciting current in phase with the load current.

IV—Determination of the Transformer Constants

Resistance. The resistance of the secondary circuit is as follows:

Secondary winding	0.62 ohms
Leads to the oscillograph (negligible)	
Vibrator of the oscillograph	0.6 "
Total secondary resistance	1.32 "

Reduced to the primary the equivalent resistance is 13,200 ohms.

The resistance of the primary is 6600 ohms, making a total transformer and vibrator resistance of 19,850 ohms.

It will be noted that the resistance given for the vibrators, (0.6 ohms), is only one-half of the resistance of the standard vibrators. This reduction in the resistance has been effected by modifying the vibrators as shown in Fig. 6. This modification eliminates useless silver strip, reducing the length of the strip to one-half the standard length, without in any way affecting the period or sensitiveness of the vibrator. It is of course out of the question to fuse vibrators used in the secondary of the current transformer, because of the high resistance of the fuse.

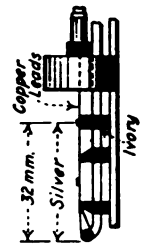


Fig. 6—Modified Vibrator

Reactance. The reactance of the external part of the secondary circuit is negligible in comparison with the reactance of the secondary winding.

The separate reactances of primary and secondary due to leakage flux cannot be computed from the transformer dimensions with any degree of accuracy. The combined leakage reactance of primary and secondary can, however, be obtained experimentally by taking an oscillogram with the connections shown in Fig. 7. Fig. 8 (film 203) is a characteristic oscillogram taken with these connections. The current I in the secondary lags about 12 degrees

behind the potential E across the primary. With a transformer and a vibrator resistance of 19,850 ohms, a lag of 12 deg. indicates a leakage reactance of 4800 ohms at 60 cycles.

It will be approximately correct, and will introduce no appreciable error to apportion half of this to the primary and half to the secondary, thus making the primary reactance 2400 ohms and the secondary reactance 0.24 ohms. Fig. 5 has been constructed on this basis.

Flux Densities. With a total secondary impedance of 1.33 ohms = $(1.32 + j\,0.24)$, the secondary voltage at 0.05 ampere is 0.066 volt. To generate this voltage, the flux densities must be 36 lines per sq. cm. in the bridge and 10 lines per sq. cm. in the wings. Data are not available for the predetermination of the exciting current at these low flux densities.

Phase Displacement and Ratio of Transformation. To determine the phase displacement between primary and secondary

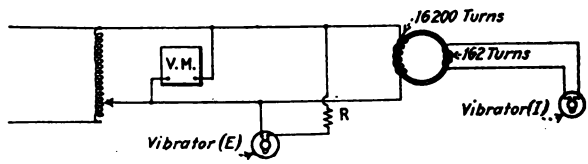


FIG. 7—CONNECTIONS FOR THE DETERMINATION OF TRANSFORMER REACTANCE

currents and the ratio of transformation, oscillograms were taken with the connections shown in Figs. 9 and 12. As shown in Fig. 9, a 60-cycle current, measured by a voltmeter A, is passed through one of the 81-turn coils and through the vibrator P. The second 81-turn coil is connected through an adjustable resistance R to the vibrator S, which was calibrated before and after these tests.

For small variations in the resistance of the secondary circuit, the angle of phase displacement and the percentage reduction in the multiplier are approximately proportional to the secondary resistance. The additional resistance R, which was varied from zero to three ohms, was inserted for the purpose of increasing the angle of phase displacement, thus permitting of its more accurate determination from the films. Figs. 10 (film 200) and 11 (film 201) are characteristic films obtained in this manner. By scaling the films, it is found that the transformer with an 81-turn secondary has a ratio of transformation 3.2 per cent less

mining the order of magnitude of this current, assume the primary is wound evenly in layers, each layer starting from the same side of the spool. With a wall thickness of 0.008 mm. of enamel insulation surrounding each wire, the estimated capacity between adjacent layers is less than 8×10^{-9} farads, or the capacity reactance to 60 cycles is 340,000 ohms. With 0.0005 ampere in the primary the voltage between layers is 0.13 volt and the displacement current between layers will be 4×10^{-7} ampere or 0.08 per cent of load current.

The first two transformers constructed were wound with 40,000-turn (5 miles of wire) primary coils of 0.08-mm. enameled wire. For these transformers the displacement current between layers, computed under the assumption of uniform layers, was 0.2 per cent of the load current. This seemed low enough, and accordingly the transformers were wound with no additional insulation between layers. As noted in the introduction, these transformers were designed for a ratio of approximately 100, but on test developed a ratio of only 89; moreover, higher harmonics were not faithfully reproduced in the secondary. For some time the cause of this discrepancy between computed performance and performance on test could not be discovered. Finally, in unwinding one of the transformers the observation was made that the nth turn was not always adjacent to the ($n-200$th) and ($n+200$th) in the preceding and following layers,—as would be the case with uniform layers, and as assumed in the computations,—but occasionally came in contact with turns farther removed from it, as the ($n \pm 900$th) or the ($n \pm 1400$th). The explanation of this is as follows:

In winding a fine wire the turns have a decided tendency to override and "pile up" several turns deep at some parts of the layer, and to run ahead of the correct position at other parts. Where the wire runs ahead of its correct position, a portion of the lower layer is left uncovered, with the result that turns in the neighborhood of the ($n \pm 900$th) or ($n \pm 1400$th) turn may come in contact with these uncovered portions of the lower layers. The difficulty of winding in absolutely uniform layers is so great that the wire was allowed to pile up and run ahead in this manner. After observing this condition of the winding it became evident that the loss in primary ampere-turns might be far higher than the 0.2 per cent computed for uniform layers; this loss in ampere-turns would be due to the "bridging" of sections of the winding at considerable difference

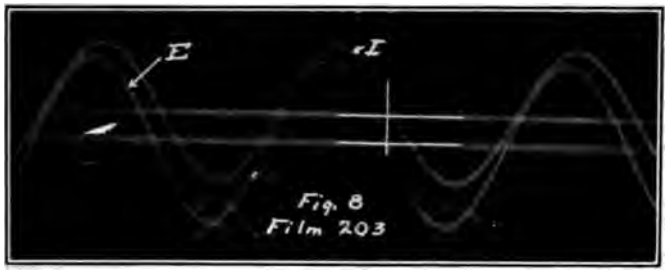


FIG. 8 [BENNETT]

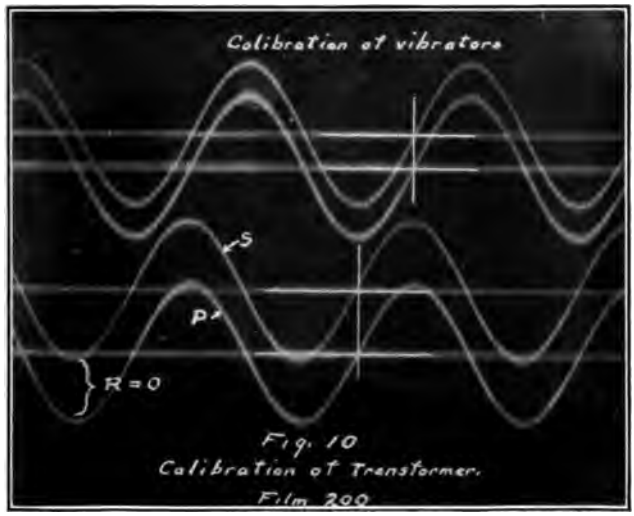


FIG. 10 [BENNETT]

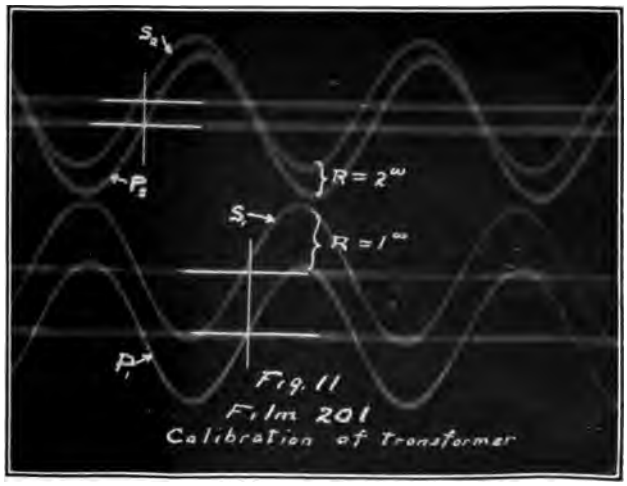


FIG 11 [BENNETT]

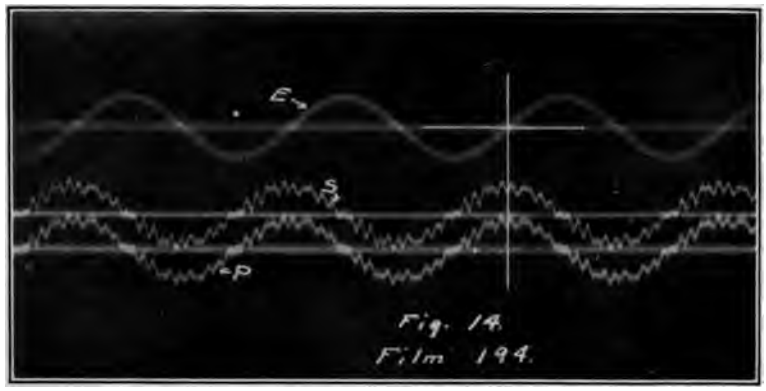


FIG. 14 [BENNETT]

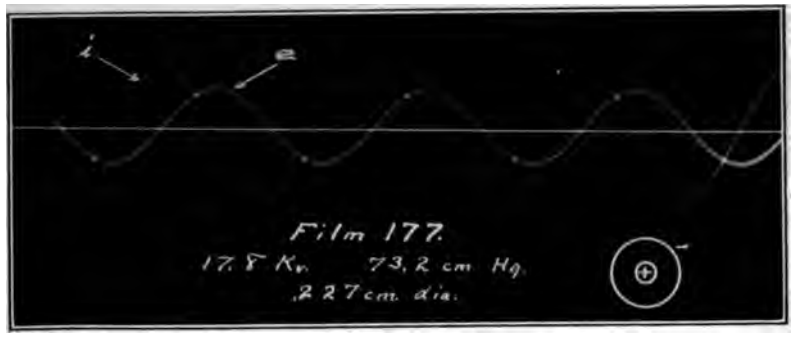


FIG. 17 [BENNETT]

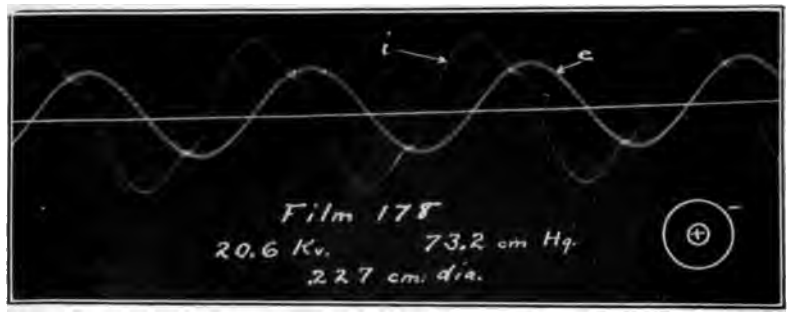


FIG. 18 [BENNETT]

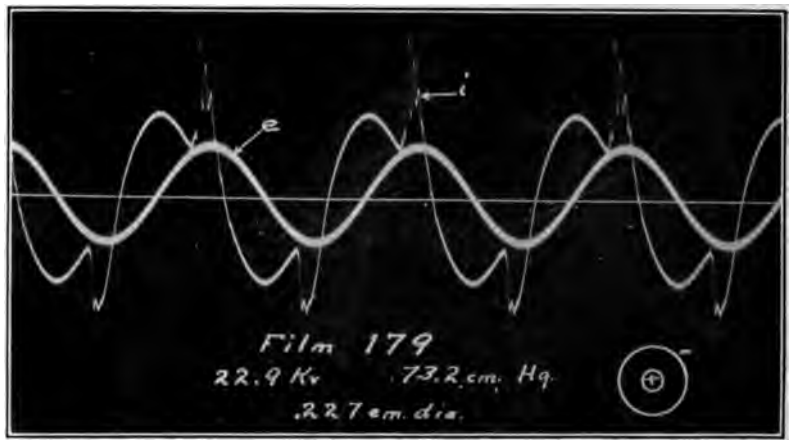


FIG. 19 [BENNETT]

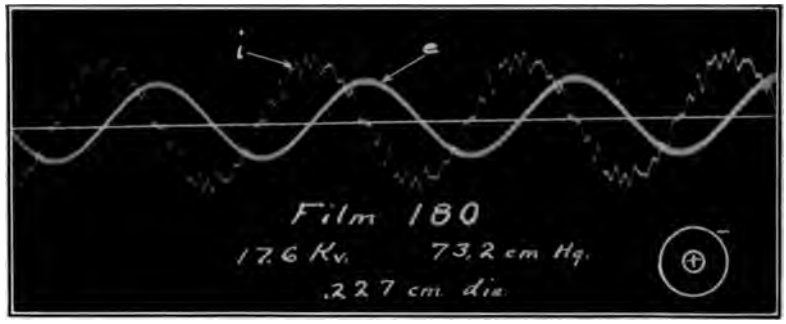


FIG. 20 [BENNETT]

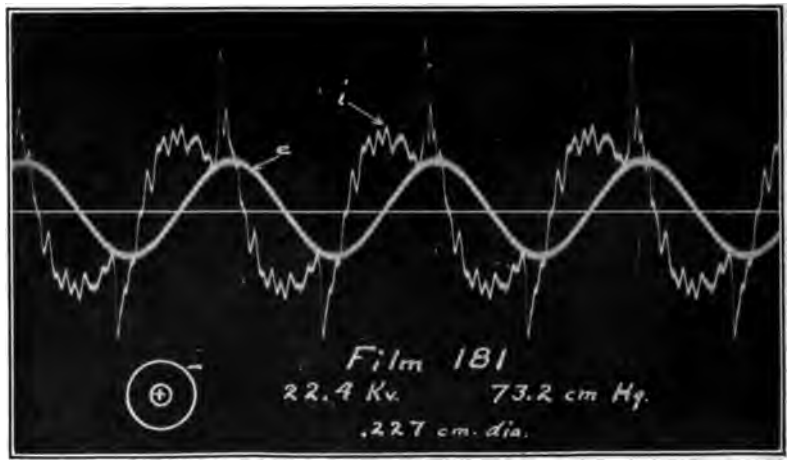


FIG. 21 [BENNETT]

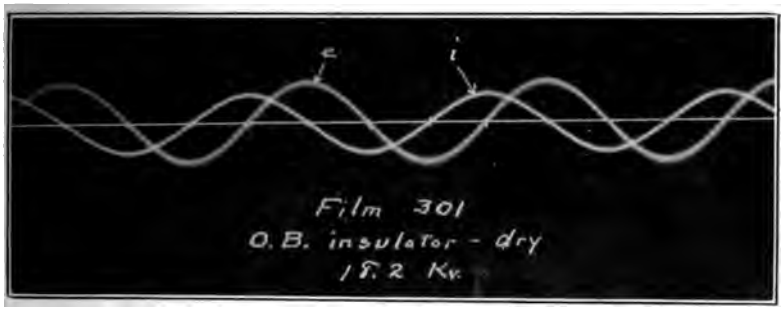


FIG. 25 [BENNETT]

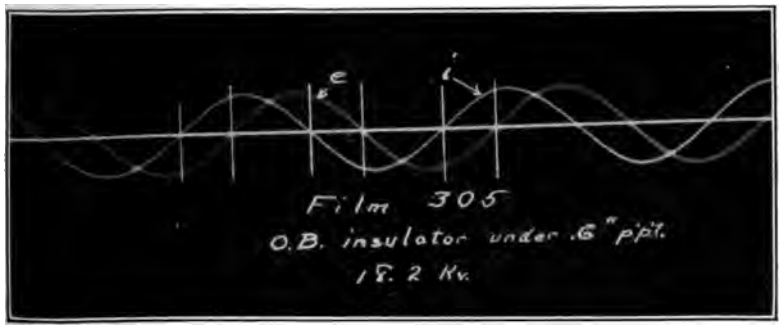


FIG. 26 [BENNETT]

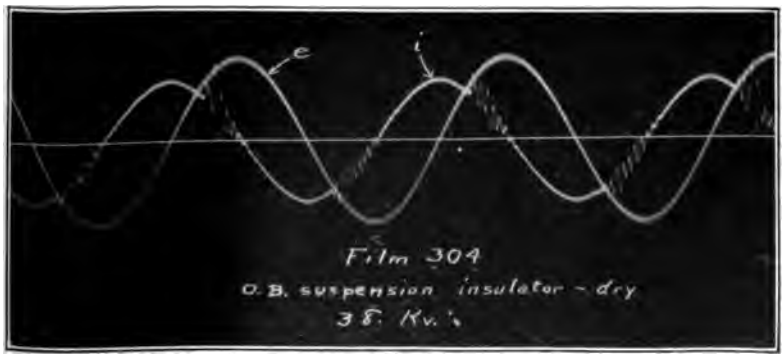


FIG. 27 [BENNETT]

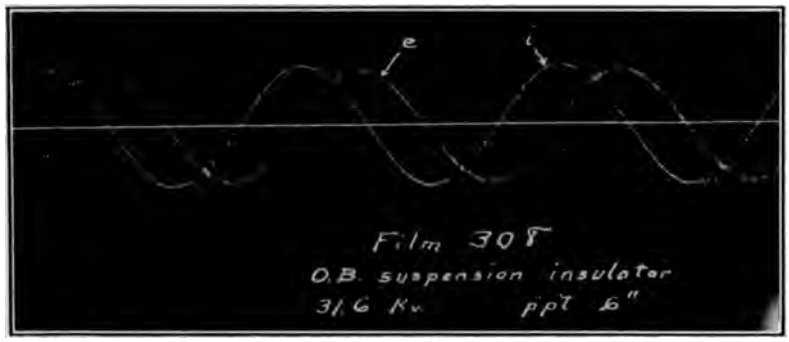


FIG. 28 [BENNETT

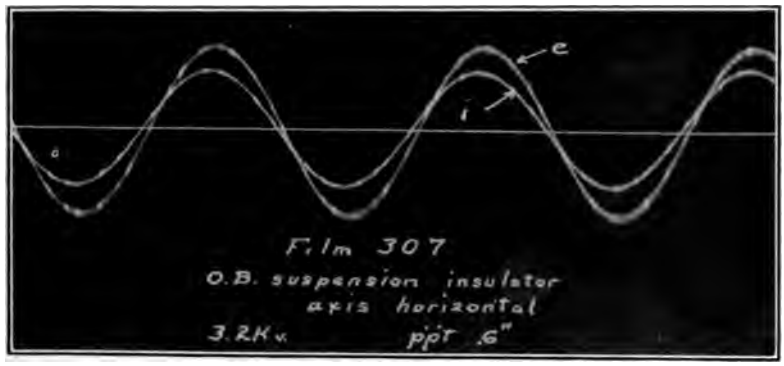


FIG. 29 [BENNETT]

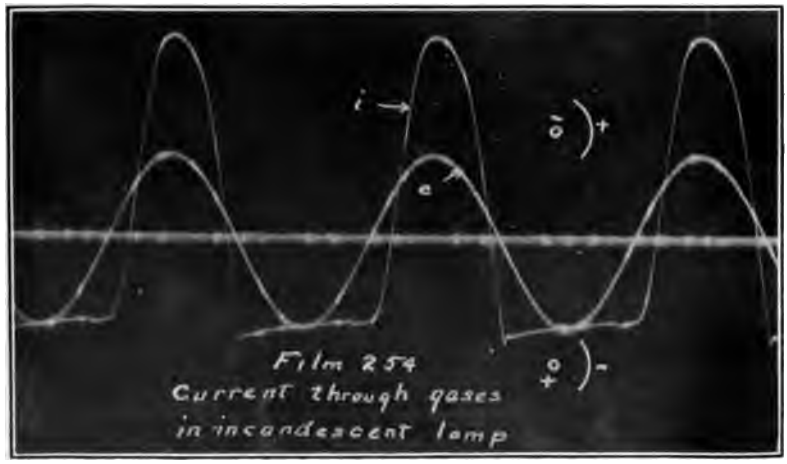


FIG. 30 [BENNETT]

of potential by the capacity between the turns in contact. The displacement current between these sections in contact would be shunted from the portion of the winding between the turns.

The use of paper insulation between layers is a remedy which immediately presents itself. A layer of paper between each two layers of wire would result in a primary coil with a much larger mean diameter. This in turn means a very appreciable and objectionable increase in the leakage reactance.

The primary of the transformer described in this paper was accordingly wound in sections of about 600 turns each, with paper insulation between the sections only. Each section was the full width of the coil and on the average three turns deep. The winding of a section started at one face of the spool, advanced toward the other face, the turns piling up two to four deep all along, and terminated when the other face of the spool was reached. A single thickness of 0.04-mm. tissue paper was wrapped around the completed section, and the next section was wound on this paper, and so on. Wound in this manner, there is no possibility of the nth turn coming in direct contact with a turn any farther removed from it than the ($n \pm 50$th). By winding and insulating the transformer in the manner described, it is estimated that the integrated effect of the 60-cycle current shunted from the primary winding has been reduced to less than 0.02 per cent of the total primary ampere-turns.

The importance of reducing the shunting effect of capacity between layers to this low value at 60 cycles, is realized when considering the magnitude of the effect for the higher harmonics, for example, the fifteenth. The capacity reactance between turns, layers and sections to the 15th harmonic is 1/15 of the reactance to 60 cycles; the impedance to the passage through the windings of the 15th harmonic in the current is approximately five times the impedance to 60 cycles; therefore, the percentage of the 15th harmonic shunted from the windings will be 75 times the percentage of the fundamental shunted.

If, then, less than 0.02 per cent of the 60-cycle current is shunted from the windings, the percentage of the 15th harmonic will be less than 1.5 per cent. The conclusion is that the influence of displacement currents within the primary winding may be neglected for the fundamental and any harmonic not higher than the 15th.

To check the preceding conclusions relating to higher harmonics in the current wave form, an oscillogram, Fig. 14,

(film 194) was taken with the connections shown in Fig. 15. In Fig. 15, B is a Leyden jar condenser having about 100 times the capacity of the condenser C, which consists of two concentric cylinders separated by air,—a steel wire 0.059 cm. in diameter in a 518-cm. length of pipe of 20.6 cm. diameter. Both condensers in parallel were connected across a high-tension transformer generating 9.6 kv. The charging current of the Leyden jars B was sent through the vibrator P and the charging current of the cylinder condenser C was sent through the primary of the current transformer, the secondary being connected to the vibrator S. The vibrator E shows the potential wave form across the primary of the transformer. The charging current of the two condensers B and C should have the same wave form, and any appreciable errors introduced by the transformer should cause an appreciable difference in

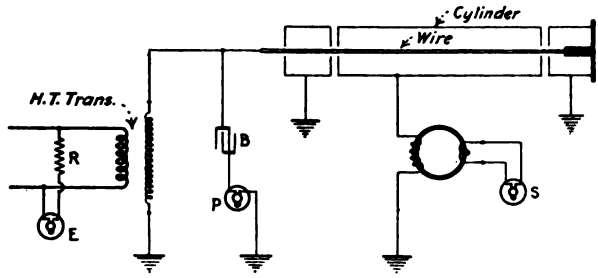


FIG. 15—CONNECTIONS TO SHOW THE REPRODUCTION OF HARMONICS

the shape of the current wave forms P and S. An examination of the oscillogram shows that the harmonics in the primary of the transformer are very faithfully reproduced in the secondary.

V. APPLICATIONS

The transformer extends the field of usefulness of the oscillograph by increasing a hundred fold its current sensibility. This makes it possible to use the oscillograph in fields from which it has hitherto been barred by reason of the minuteness of the currents to be studied. In this connection, however, it should be recalled that a current transformer cannot increase the watt sensibility of the oscillograph, and that the actual watt sensibility of the combined current transformer and oscillograph is thirty per cent of the watt sensibility of the oscillograph alone. Consequently, the current trans-

former can only be used where the current to be investigated flows under a voltage high as compared with the voltage consumed in the transformer. This voltage is of the order of ten volts for 0.0005 ampere. Figures 17 to 30 are oscillograms intended to show some of the applications of the combined current transformer and oscillograph.

Application to Corona Studies. The oscillograms, Fig. 17 to Fig. 21, (film 177 to 181), taken with the connections shown in Fig. 2, show the effect of corona formation on the charging current of a wire. The metal cylinder of Fig. 2 was an 8-in. (20.6-cm.) iron pipe 17 ft. (518 cm.) long, in the center of which was stretched a polished copper wire having a diameter of 0.227 cm. Corona is visible around this wire at 18.7 kv.

Fig. 17 (film 177) was taken at 17.8 kv.—below the voltage at which corona is visible.

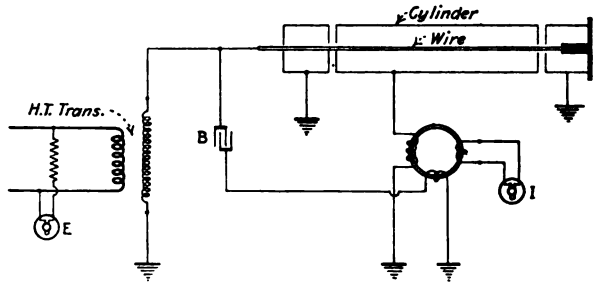


FIG. 16

Figs. 18 and 19 (films 178 and 179), were taken above the corona voltage at the voltages indicated on the films. They show: (a) the point on the e.m.f. wave form at which copious ionization sets in, (b) the duration of the period of ionization, (c) the asymmetrical nature of the process of breakdown. In all these films a positive current is a current from the pipe to the wire, or the wire is cathode for positive deflections.

The three films above referred to were taken with a combination of inductance and capacity in the circuit adjusted to "weed out" all harmonics from the generator wave form. The next two oscillograms, Figs. 20 and 21 (films 180 and 181), were taken with the same wire but without "weeding out" the harmonics from the impressed voltage.

To show more clearly the characteristics of the current which flows when corona forms, the connections shown in Fig. 16 may be used. In Fig. 16, the charging current from a con-

denser B, connected between wire and ground, is sent through one of the secondary coils of the current transformer in such a direction as to oppose the magnetomotive force of the primary current.

The capacity of the condenser B is adjusted so that its charging current neutralizes the charging current between wire and pipe for all voltages below the formation of corona. When corona forms, the two currents no longer balance, and the deflection of the current vibrator shows the current which is superimposed on the charging current as the result of the ionization. Figs. 22 and 23 (films 188 and 189), were taken with Fig. 16 connections, with a 0.059-cm. steel wire in the 8-in. pipe.

The asymmetrical nature of the current is more striking at low gas pressures than at atmospheric pressure. This is in-

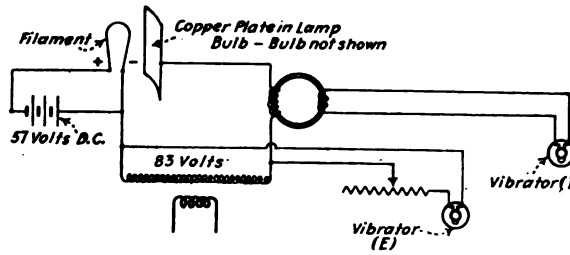


FIG. 31

dicated in Fig. 24, (film 224), an oscillogram obtained with a 0.102-cm. phosphor-bronze wire in the 8-in. pipe of Fig. 2.

This oscillogram was obtained with the pipe closed at the ends and exhausted to a pressure of 0.5 cm. of mercury.

Application to Insulator Investigations. The current transformer may be used to determine the charging and leakage currents of high-tension insulators and the ohmic resistance of wooden pins at high voltages.

With the connections shown in Fig. 1 the oscillograms in Figs. 25 to 29 were taken on a 10-in. (25.4-cm.) suspension insulator.

Figs. 25 and 26 (films 301 and 305) were taken at 18.2 kv., with the insulator dry and under spray, respectively. The spray was directed downward at an angle of 45 deg. from the vertical; the rate of precipitation was 0.6 in. (1.5 cm.) per minute. The 60-cycle charging current of the dry insulator at the rated voltage, eight kv., is 2.16×10^{-4} (r. m. s.) amperes, indicating a capacity of 3.14×10^{-11} farads. Under spray,

Fig. 26, the current leads the potential by only 70 deg., or the resistance of the insulator drops to 180 megohms.

Figs. 27 and 28 (films 304 and 308) show the charging current at a voltage high enough to cause streamers over a part of the insulator surface. The oscillograms were taken with the insulator dry at 38 kv. and under spray at 31.6 kv., respectively. For positive currents the insulator pin is cathode and the metal cap is anode.

Fig. 29 (film 307) is an oscillogram taken on a 10-in. (25.4-cm.) suspension insulator under spray, with the axis of the insulator horizontal. The insulator resistance is only seven megohms.

Application to the Study of Conduction in Gases. The transformer may be used to determine the wave form of the minute leakage currents between electrodes in gases at low pressures.

Fig. 30 (film 254) shows the wave form of the current through the gas between an incandescent carbon filament and a copper plate mounted in the evacuated bulb of an incandescent lamp.

The filament was a 55-volt 16-c.p. filament, operated at 57 volts on direct current. A 60-cycle alternating voltage of 83 r.m.s. volts was impressed between the copper plate and one terminal of the filament; the connections are as shown in Fig. 31. In interpreting this oscillogram, it should be recalled that the average value of the current delivered by the secondary of the current transformer will be zero, irrespective of the wave form of the primary current. The negative branch of the current wave does not mean that the primary current flows from the incandescent filament anode to the copper plate cathode. The primary current is unidirectional and only flows during the half-cycle in which the filament is cathode. No appreciable current flows when the cold copper plate is negative to the filament; the current shown by the oscillogram during this half-cycle is only an apparent current; it is due to the shift of the secondary current wave form with reference to the primary current wave. Both wave forms are similar, but the primary is unidirectional, while the average of the secondary must equal zero.

Discussion on "A Milliampere Current Transformer" (Bennett), Washington, D. C., April 25, 1914.

J. B. Whitehead (by letter): In conjunction with Professor Bennett's paper* last year at Cooperstown, the present paper completes a description of the equipment with which he has obtained his interesting and valuable results on the corona. The transformer which he describes, by offering a means for measuring the corona current, should open up a wide field of investigation. The possibility, as demonstrated by Professor Bennett, of neutralizing the charging current is especially valuable.

One or two questions suggest themselves:

As the scale of the diagram for Fig. 5 is evidently not the same for all vectors, I have not been able to understand the statements at the top of the following page.

The statement is made on the next page thereafter, under the heading "Phase Displacement and Ratio of Transformation," that the phase displacement and percentage reduction in the multiplier are proportional to the secondary resistance. I shall be glad to have further elucidation here.

Referring to Fig. 15, since presumably all the vibrators were in one oscillograph, the question of potential difference arises, unless each vibrator was grounded.

J. R. Craighead (by letter): The specific features of design of a current transformer should be determined by the uses to which it is to be put. In Mr. Bennett's transformer, the primary winding is made of wire several times larger than would be needed on a heating basis, in order to keep the total impedance low. More accurate transformation of the current can be secured by using much smaller primary wire, thus increasing the ampere-turns or diminishing the mean length of magnetic circuit. This will be accompanied by an increase in the impedance and I^2R losses of the transformer which would be objectionable only for circuits of comparatively low voltage.

It should be emphasized that the current transformer is accurate only when carrying a true alternating current. When supplied with a current containing a direct-current component, it operates in a different range of flux density because of the constant magnetizing effect of the direct current, and the errors are largely increased. If a current transformer under normal conditions has from 2 to 5 per cent exciting current, the presence of a 50 per cent direct-current component therefore may readily give a direct magnetomotive force from 7 to 17 times as great as the maximum under operating conditions. Calculations of errors with alternating current alone cannot therefore be relied on to determine accuracy with pulsating

* "An Oscillograph Study of Corona", Trans. A.I.E.E., Vol. XXXII, 1913, p. 1787.

currents. The alternating components of transients and rectified or partially rectified currents will not be accurately shown.

The alternative is the use of vibrators of higher current sensitivity. These are available of about 10 times the sensitivity of the standard vibrator, and consume about the same energy. This will cover satisfactorily many cases where the transformer would give inaccurate results, but will not reach to the extremely low values covered by the transformer.

Edward Bennett (by letter): With reference to the questions raised by Dr. Whitehead: In the vector diagram of Fig. 5 the exciting current I_e and its components I_m and I_w are drawn to ten times the scale of the primary and secondary currents. The voltage which must be generated by the magnetic flux in the iron, in order to set up the full load current through the secondary winding, will be directly proportional (approximately) to the total secondary resistance, since the reactance is negligible. The exciting current necessary in the primary to set up with magnetic flux will be approximately proportional to the flux and since the flux is proportional to the secondary resistance, therefore the exciting current will be directly proportional (approximately) to the total secondary resistance. An inspection of the diagram will show that the exciting current will remain less than 5 per cent of the neutralizing current I_n for a reasonable variation in the secondary resistance. Under these conditions a study of the diagram will show that since the exciting current is directly proportional to the total secondary resistance, therefore "for small variations in the resistance of the secondary circuit, the angle of phase displacement and the percentage reduction in the multiplier will be approximately proportional to the secondary resistance."

In Fig. 15 the terminal of vibrator P is grounded and the vibrator S is ungrounded. One terminal of the primary of the current transformer to which the vibrator S is connected is grounded and the average potential of the primary from ground is less than 6 volts, therefore the potential of the vibrator S will probably differ from ground potential by less than 2 volts.

Mr. Craighead's comments apply more particularly to the characteristics of instrument transformers in which flux densities from 500 to 2000 lines per square centimeter are in use. In the milliampere current transformer, in which the maximum flux density is only 36 lines per square centimeter, we encounter features of design that are entirely negligible in the commercial transformer. For example, very little improvement indeed can be made in the characteristics of the milliampere transformer by increasing the number of turns in the winding:

First: Because the permeability decreases rapidly for flux densities below 50 lines per square centimeter, so that very little is to be gained by using a lower flux density.

Second: Because an increase in the number of turns will increase to such an extent the component of the current which gets through the primary as displacement current from layer to layer, that high harmonics in the primary will not be faithfully reproduced.

Third: A material increase in the number of turns cannot be made without increasing either the length of the magnetic circuit or the resistance of the secondary.

Again, it would seem that the caution with reference to the use of the current transformer with pulsating currents can hardly be taken to imply that the oscillograms showing the presence of a large unidirectional component are appreciably in error. Even if the unidirectional component of the primary current exerted a magnetomotive force 17 times the exciting m.m.f., this would only lead to a unidirectional flux of 17 times 36, or 612 per square centimeter, on which would be superimposed a cyclic change of $\pm$ 36 lines per square centimeter. Under these conditions the wave form of the pulsating current would be faithfully reproduced in the secondary. As pointed out, however, in the paper, the wave form of the secondary current will, under these conditions, be so displaced with reference to the zero line as to make the average value of the secondary current zero.

Presented at the 294th meeting of the American Institute of Electrical Engineers, Washington, D.C., April 25, 1914, under the auspices of the Electrophysics Committee.

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THEORY OF THE CORONA

BY BERGEN DAVIS

ABSTRACT OF PAPER

The theory of the corona developed in this paper explains the coronal discharge by the application of the known laws of the discharge of electricity through gases.

The experiments of Dr. Whitehead and Mr. F. W. Peek and others have shown that the surface gradient X_s at the surface of a smooth wire necessary to start the corona increases very greatly as the radius of the wire decreases. As an illustration of this increase it is found that the coronal gradient X_s at the surface of a wire of 0.5 cm. radius is 46,000 volts per cm., while a gradient of 97,000 volts per cm. is required for a wire of 0.02 cm. radius. The phenomenon is due to ionization by impact. The ions n_0 move in toward the wire from the place at which they cross a region where the gradient is X_0 = 26,600 volts per cm. up to the wire. They produce other ions, and n ions arrive at the wire. The condition for the corona is that n shall be a constant. If α = the number of ions that one ion produces in a cm., then

$$n = n_0 e^{\int_a^b \alpha \, dx}$$

The α is a function of X at every point. This function is expressed in terms of x. It is introduced into the above equation, and on integration the equation for the corona is obtained. The equation also contains a term for the density of the air. The equation thus takes account of changes of pressure such as altitude and temperature effects. The equation when plotted in a curve for the variation of X_s with the radius of the wire, agrees with the experimental results of Whitehead and Peek with as great accuracy as the experimental results would warrant.

THE ATTENTION of the writer was first called to the coronal discharge from high-tension transmission lines by a paper presented to the American Institute of Electrical Engineers in 1911 by Prof. H. J. Ryan[1]. This discharge is a very interesting one from the point of view of the discharge of electricity through gases. The phenomena have been quite fully investigated and described by Dr. J. B. Whitehead, F. W. Peek and others.

When either a direct or an alternating high potential is applied to a smooth cylindrical conductor, there is at the surface of the wire a very high gradient of potential or electrical intensity.

1. TRANS. A. I. E. E., Vol. XXX., 1911, p. 1.

When this electrical intensity becomes great enough, the surrounding dielectric, in this case air, breaks down and a faint glow appears, and, as has been shown by Dr. Whitehead, the air becomes ionized. If the electrical intensity is still further increased, the ionization and luminosity increase also, and there is considerable loss of energy from the wire.

There are interesting relations between the surface gradients necessary to produce the corona and the radius of the wire. As the radius decreases, the electrical intensity increases very much, as is shown by the curves in Figs. 3 and 4. In a discussion of this effect Dr. Steinmetz has suggested that there is a skin effect at the surface of a conductor; that the dielectric strength of air is altered by contact with a curved metal surface. It appeared to the writer that this could not be the case, but rather that this phenomenon should be capable of explanation by the known laws of the discharge of electricity through gases. The following development of a theory of this effect appears to show that it is really a case of ionization by impact.

The theory of ionization by impact has been developed by Prof. J. S. Townsend. He has established by experiments, that if α is the number of new ions produced in a gas by one ion in going one centimeter when driven by an electrical intensity X, and p is the pressure of the gas, the following functional relation holds between α, x and p, for all values of α, x and p whatsoever:

$$\frac{\alpha}{p} = f\left(\frac{X}{p}\right) \tag{1}$$

When ionization by impact takes place in a gas, the density of ionization is enormously increased, as is shown by the following considerations. Let n_0 be the number of free negative ions crossing a unit of area of surface in a gas in unit time, under an electrical intensity X. Let α be the number of ions produced by one negative ion in going one centimeter.

If the ion moves a distance dx, the number produced will be $\alpha\, dx$, and if there are N such ions crossing any plane, the number crossing a plane dx distant will be $dN = \alpha\, Ndx$. On integrating this between n_0 crossing plane of start of the action, and n, the number crossing a plane at distance d, we have:

$$\frac{n}{n_0} = e^{\int_0^d \alpha\, dx} \tag{2}$$

If the electrical intensity is uniform between a and d, α is independent of x and the equation becomes

$$\frac{n}{n_0} = e^{\alpha d}, \text{ which is that used by Prof. Townsend.}$$

The conditions about a cylindrical conductor may be described by use of the cross-section of such conductor represented by Fig. 1.

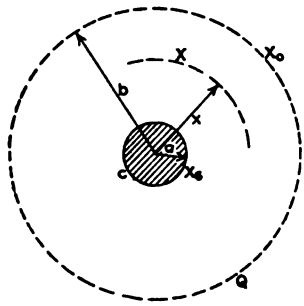

FIG. 1

The shaded portion c represents the conductor, whose radius is a. The electrical intensity at the surface of this conductor is X_s, and X represents the electrical intensity at any point distant x from the center of the conductor.

The cylindrical surface Q, whose radius is b, represents the surface where the electrical intensity has the constant value X_0. This electrical intensity X_0 is the least gradient of potential at which ionization by impact can occur. Ionization by impact and the coronal discharge itself can only take place between the surface Q and the wire, in which region the electrical intensity is greater than X_0.

Let E represent the potential difference between the wire and the ground or some other distant conductor, and let the distance of this other conductor or ground be R.

The electrical intensity at x is

$$X = \frac{E}{x \log \frac{R}{a}}$$

At surface it is

$$X_s = \frac{E}{a \log \frac{R}{a}}$$

At surface Q it is

$$X_0 = \frac{E}{b \log \frac{R}{a}}$$

From the above we obtain

$$X = X_0 \frac{b}{x}, \text{ and } X_s = X_0 \frac{b}{a}. \tag{3}$$

The physical process involved in the establishment of the discharge may be traced in the following way: The conductor is subject to an alternating potential. Let the maximum value of this at crest of the wave be just sufficient to produce the corona. There are a certain number of ions, N_0, in the region around the wire. Only negative ions ionize by impact at ordinary pressures. Suppose the wire to be at the positive phase, the N_0 ions move inward and when they cross the surface X_0 they begin to ionize by impact. They produce N_1 ions which approach the wire. Here some of the N_1 ions disappear (current loss). On the next phase, the wire is negative, these ions move outward from the wire. Some of them disappear by recombination, but there are N_{01} left, and N_{01} is much greater than the original N_0. These N_{01} ions move inward on the succeeding positive phase. They produce N_2 ions, which on the next half phase decrease to N_{02} ions, and thus the process goes on until, after a number of cycles, the density of ionization about the wire at crest of positive phase is n. The n_0 in the theory here proposed is the number of ions crossing the surface X_0 on the phase at which the discharge appears.

Now let n_0 be the number crossing the surface where the intensity is X_0, and let n be the number which reach the surface of the wire, and assume also that the visible discharge appears when n reaches a fixed constant value.

From equation (2),

$$\frac{n}{n_0} = e^{\int_a^b \alpha\, dx} \tag{4}$$

The density of ionization at surface of conductor will increase somewhat, without ionization by impact, as the N_0 ions move inward. This increase will be proportional to the ratio of the radius of surface Q to that of the conductor.

We may now write

$$\left(\frac{n}{n_0}\ \frac{a}{b}\right) = e^{\int_a^b \alpha\, dx} \tag{5}$$

One may assume that the discharge will appear when the ionization per unit area at the surface reaches a certain constant value n.

An inspection of Fig. 1 will also show that the number of n_0

ions, crossing surface Q per unit area, varies inversely as b; consequently, we may approximately assume that the whole term on the left is a constant for first appearance of discharge.

$$\text{Constant} = \left(\frac{n}{n_0} \frac{a}{b}\right) = e^{\int_a^b \alpha\, dx} \tag{6}$$

The number of new ions α that one ion produces in going one centimeter is a function of X, by equation (**1**), and X is a function of x by equation (**3**), so that α is a function of x. It is necessary to express this function in order to perform the integration indicated in the right-hand member of equation (**6**).

The number of ionizing impacts per cm. indicated by α in the right-hand member of (**6**) depends upon the value of the electrical intensity X, which in turn depends on the distance x from center of conductor (see Fig. 1). Consequently, α will depend upon x. Also, α depends upon the pressure of the air.

Since we find that α is a function of x and p, it is necessary to express the form of this functional relation.

A few years ago, the writer[2] developed a theory of ionization by impact, by means of which the form of the function

$$\frac{\alpha}{p} = f\left(\frac{X}{p}\right), \text{ may be expressed.}$$

The complete development of this function cannot be given here, but the reader is referred to the original paper.

The expression there obtained for α is

$$\alpha l = e^{-\frac{\lambda_0}{l}} + \frac{\lambda_0}{l} E i\left(-\frac{\lambda_0}{l}\right) \tag{7}$$

where λ_0 is the least ionizing path of an ion when driven by a field X, and l is the mean free path of the negative ion at the pressure considered. The least possible difference of potential through which an ion must freely run to produce ionization is $v = X\lambda_0$. The quantity $X\lambda_0$ should be a constant for any gas, independent of the pressure and independent of the electrical intensity.

2. *Physical Review*, Jan. 1907, also *Annalen der Physik, Band* **42, 1913.**

Recent experiments by Bishop[3] show this to be the case, and the value he finds for v in case of air is $v = 10.2$ volts.

Equation (7) very easily transforms into the following expression:

$$\frac{\alpha}{p} = \frac{1}{76\,L}\left[e^{-\frac{v}{76\,L}\frac{p}{X}} + \frac{v}{76\,L}\frac{p}{X}\,Ei\left(-\frac{v}{76\,L}\,\frac{p}{X}\right)\right] \qquad (8)$$

where $v = X\lambda_0$, p is the pressure of the air in cm. of mercury, and L is the mean free path of an ion at normal pressure.

The above equation expresses the form of the function

$$\frac{\alpha}{p} = f\left(\frac{X}{p}\right).$$

If the value of α from this expression is introduced into equation (6), and likewise the values of X in terms of x are introduced from (3), we will have a complete expression for the appearance of the corona, at any pressure and for any size of conductor. However, equation (8) is not directly integrable for x. It contains the exponential integral

$$Ei\left(-\frac{v}{76\,L}\,\frac{p}{X}\right)$$

which is a series, every term of which would need to be separately integrated, for every case. This equation is consequently unworkable.

An integral equation which is a close approximation to (8) must be found. Equation (9) is such an expression. Its departures do not introduce any considerable errors, particularly for values of $\frac{X}{p}$ less than 900.

The approximate equation is

$$\frac{\alpha}{p} = A + B\left(\frac{X}{p} - 350\right)^2 \qquad (9)$$

If the constants A and B are given the values 0.05 and 0.0000115 respectively, a good agreement of (9) and (8) is obtained, as shown by the curves in Fig. 2.

3. *Physical Review*, Nov. 1911.

By setting $X_0 = 350\ p = 26{,}600$ volts per cm., equation (**9**) becomes

$$\alpha = A\ p + B\frac{p}{p^2}\left(X - X_0\right)^2$$

Also, from equation (**3**), the above becomes

$$\alpha = A\ p + B\ p\ \frac{X_0^2}{p^2}\left(\frac{b}{x} - 1\right)^2 \tag{10}$$

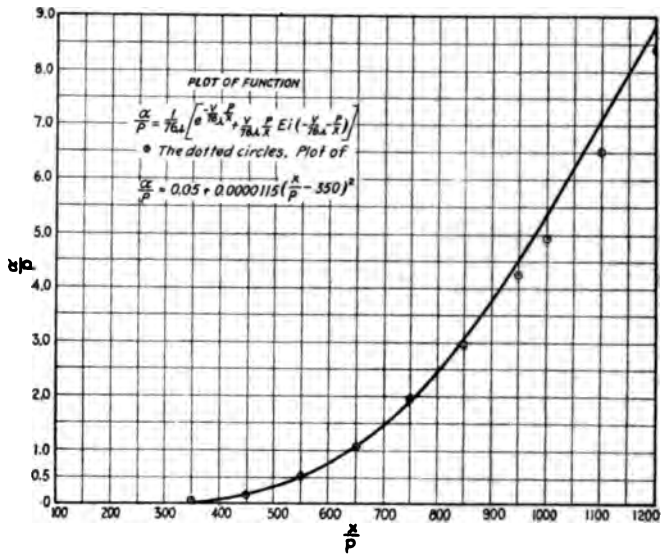

FIG. 2

It is to be noted that X_0 is the electrical intensity at points indicated by the dotted circle Q in Fig. 1. It is the least gradient at which ionization by impact can occur. Also X_0 depends on the pressure in such a way that $\frac{X_0^2}{p^2} = C$ is a constant independent of the pressure. It has the numerical value $(350)^2 = 122{,}500$ volts per cm.

Equation (**10**) becomes

$$\alpha = A\ p + B\ C\ p\left(\frac{b}{x} - 1\right)^2 \tag{11}$$

This expression for α is introduced into equation (**6**)

$$\int_a^b \alpha\, dx = A\, p \int_a^b dx + B\, C\, p \int_a^b \left(\frac{b}{x} - 1\right)^2 dx$$

The limits of integration are a and b, since the ionization takes place as the ions move inward from the surface of radius b to the surface of the wire of radius a.

Performing the indicated integration,

$$\int_a^b \alpha\, dx = A\, p\, (b-a) + B\, C\, p \left(\frac{b^2 - a^2}{a} - 2\, b \log \frac{b}{a}\right)$$

$$= A\, p\, a \left(\frac{b}{a} - 1\right) + B\, C\, p\, a \left(\frac{b^2}{a^2} - 1 - 2\, \frac{b}{a} \log \frac{b}{a}\right)$$

Since X_s is electrical intensity at distance a from center of wire, and X_0 is the electrical intensity at b from the center,

$$\frac{X_s}{X_0} = \frac{b}{a},$$

$$\int_a^b \alpha\, dx = A\, p\, a \left(\frac{X_s}{X_0} - 1\right)$$

$$+ B\, C\, p\, a \left(\frac{X_s^2}{X_0^2} - 1 - 2\, \frac{X_s}{X_0} \log \frac{X_s}{X_0}\right) \qquad (\mathbf{12})$$

It is desirable to introduce into the above a term representing the density δ of the air, where δ = unity for p = 76 cm.

Also note that $\delta\, X_0$ expresses the value of the least gradient at which ionization takes place for any density δ of the air.

Equation (**12**) now becomes

$$\int_a^b \alpha\, dx = 76\, A\, a\, \delta \left(\frac{X_s}{\delta\, X_0} - 1\right)$$

$$+ 76\, B\, C\, a\, \delta \left(\frac{X_s^2}{\delta^2\, X_0^2} - 1 - 2\, \frac{X_s}{\delta\, X_0} \log \frac{X_s}{\delta\, X_0}\right)$$

Upon introducing the values of the constants A, B and C, equation (**6**) becomes

$$\left(\frac{n}{n_0}\frac{a}{b}\right) = e^{3.8\,a\,\delta\left(\frac{X_s}{\delta X_0}-1\right)+107\,a\,\delta\left(\frac{X_s^2}{\delta^2 X_0^2}-1-2\frac{X_s}{\delta X_0}\log\frac{X_s}{\delta X_0}\right)} \quad (\mathbf{13})$$

The above is a general expression for the relation between the gradient X_s and the radius a of the wire for conditions necessary to produce the corona.

Writing the above in the logarithmic form, and since the left-hand member is constant, setting $\log\left(\frac{n}{n_0}\frac{a}{b}\right) = K$, one obtains

$$\frac{K}{a} = 3.8\,\delta\left(\frac{X_s}{\delta X_0}-1\right)+107\,\delta\left(\frac{X_s^2}{\delta^2 X_0^2}-1-2\frac{X_s}{\delta X_0}\log\frac{X_s}{\delta X_0}\right) \quad (\mathbf{14})$$

This final form may be conveniently used for comparison with experiments.

The relations between the radius of a smooth wire and the surface gradient necessary to produce the corona have been quite carefully investigated by Dr. Whitehead and F. W. Peek.

Whitehead[4] finds that equation (**15**) expresses the relation between X_s and a for a wire passing through the center of a surrounding cylinder.

$$X_s = 32{,}000\left(1+\frac{0.297}{\sqrt{a}}\right) \quad (\mathbf{15})$$

In Fig. 3 are plotted the relations of X_s to a as calculated from (**14**). The constant $K = 6$ is found by equating (**14**) with (**15**) for a particular value for X_s and a.

The dotted circles represent the results of experiment as expressed by the empirical equation (**15**). The agreement between theory and experiment is very satisfactory.

F. W. Peek[5] has investigated the problem for parallel wires in the open air. He also investigated the effect of spacing of the parallel wires. He finds that if the conductors are not too near, the relations between radius and surface gradient may be expressed by

$$X_s = 29{,}800\left(1+\frac{0.301}{\sqrt{a}}\right) \quad (\mathbf{16})$$

4. TRANS. A. I. E. E., Vol. XXX, 1911.
5. *ibid.*

The law of the corona for this case is the same as for a wire enclosed in a cylinder, but the electrical intensity at which it occurs is less than for the enclosed wire, as the constant outside the parentheses has a smaller value.

The theoretical equation represents this case also. The constant K has a smaller value, as the constant outside the parentheses in (**16**) is less than that in (**15**). The comparison of theory and experiment is shown in Fig. 4. The agreement here also is very good.

Reduction of Equation (14) to Form of Equation (15)

The fact that equations (**14**) and (**15**) plot into almost identical curves is evidence that the theoretical equation expresses

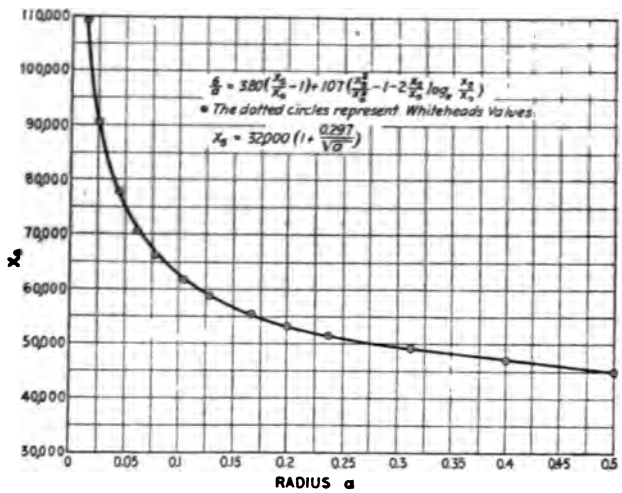

Fig. 3

the law of the corona as accurately as the empirical equations of Dr. Whitehead and Mr. Peek. However, equation (**14**) is not quite so workable in practise since it is not so simple in form and contains a logarithmic term. It is perhaps worth while to show that equation (**14**) very easily transforms into equation (**15**) if one represents the logarithmic term by a series:

$$\log_e \frac{X_s}{X_0} = C_1 \frac{X_s}{X_0} + C_2 \frac{X_0}{X_s} + C_3$$

This logarithmic term is very closely represented by the series if one gives the constants the values of 0.28, −0.82 and 0.53,

respectively. Introducing these values of C_1, C_2 and C_3 in the series, substituting the series for the logarithmic term of **(14)**, and collecting the constants of like powers of $\frac{X_s}{X_0}$, equation(**14**) immediately changes to

$$X_s = 32{,}000\left(1 + \frac{0.297}{\sqrt{a}}\right)$$

This simple transformation makes **(14)** agree in form and value with the experimental equation of Dr. Whitehead.

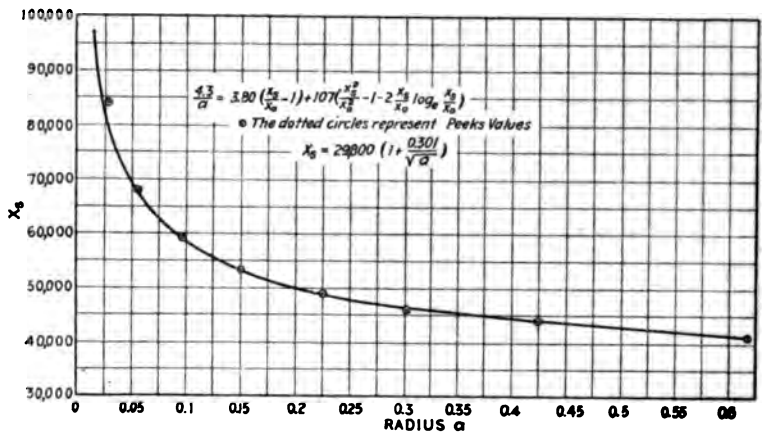

FIG. 4

CHANGE OF DENSITY OF THE AIR

Both Dr. Whitehead and Mr. Peek have investigated the effects of pressure or density of the air on the appearance of the corona. Peek points out that both his own and Whitehead's results may be represented by the following empirical equation:

$$X_s = 31{,}000\,\delta\left(1 + \frac{0.308}{\sqrt{\delta a}}\right) \qquad \textbf{(17)}$$

The term δ represents the density of the air, taking δ = unity for normal atmospheric pressure and temperature. Equation **(14)** also contains δ and consequently should also express the effect of change of density.

A plot of (**14**) is given in Fig. 5 for a few conductors of different radii, the dotted circles representing the results of experiments. Here again the agreement is very good.

Conductors Surrounded by Cylinders, and Conductors in the Open

There is a marked increase in the surface gradient required to produce the corona with the wire surrounded by a cylinder over that of a wire in the open. The experimental values of X_s are about 7 per cent greater in the one case than in the other. The theory of ionization by impact furnishes an explanation of

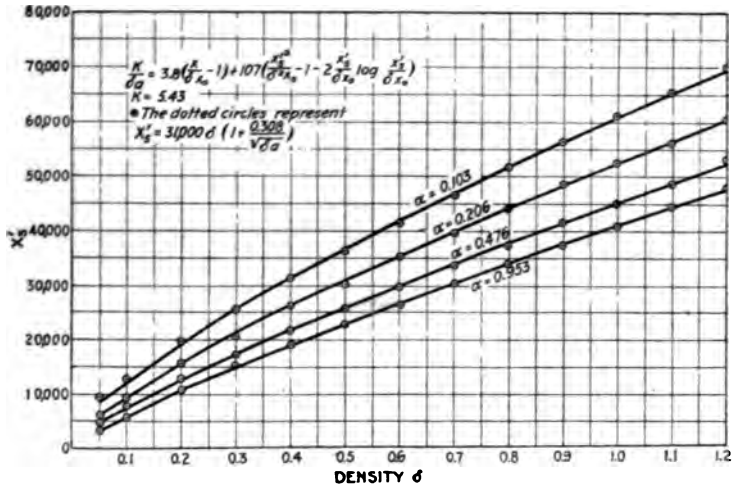

Fig. 5

this increase, as will be readily seen by a detailed study of the physical process involved in the two cases.

Consider a wire stretched through the center of a metallic cylinder, as represented in Fig. 6. The outer cylinder M, say, has a radius of 3 to 5 cm., these being the dimensions used by Dr. Whitehead. The central conductor is charged by an alternating potential, such that the gradient at the surface just produces the corona. The condition for the discharge is that the ionization n per unit area at the surface shall reach a certain value. Assume a certain amount of ionization in the cylinder, and follow the process through a cycle. The wire is just beginning its negative phase, and as the potential rises, the negative ions

are driven out from the wire toward the outer cylinder. If the radius R is small, these ions will reach the outer cylinder M and disappear before the wire changes to the positive phase. If the outer cylinder M is not there, but another wire or the earth is at a considerable distance, the ions will not have disappeared, but will still exist and many will return and cross the surface Q, on the reversal of phase. The n_0 ions of equation (13) are thus decreased by the nearness of the cylinder, and the gradient X_s is increased. One can readily calculate the change in n_0. For a wire in the open (see Fig. 4):

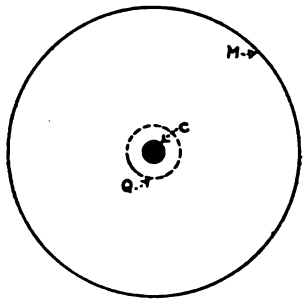

FIG. 6

$$K = \log\left(\frac{n}{n_0}\,\frac{a}{b}\right) = 4.3$$

And for a wire in a cylinder (see Fig. 3):

$$K = \log\left(\frac{n}{n_0}\,\frac{a}{b}\right) = 6$$

The ratio of a to b will be about the same in the two cases. It is found from the two expressions above that n_0 is 5.5 times as great for a wire in the open as for a wire enclosed in a cylinder.

THE EFFECT OF SPACING OF PARALLEL CONDUCTORS

Mr. Peek has observed some interesting and unexpected results of the effect of spacing of parallel conductors. It was found that at great distances, a change in spacing had no effect on the coronal surface gradient, but when the wires were brought nearer, the gradient increased, and at a certain spacing not near enough for sparking, the gradient became nearly as great as for wires surrounded by a cylinder. As an illustration, when the two parallel conductors of 0.1 cm. radius are 20 cm. apart, the gradient is 58,000 volts per cm.; when they are 7 cm. apart, the coronal gradient is increased to 61,000 volts per cm.

These results can also be explained by the assumption that part of the n_0 ions disappear when the conductors are near.

Consider the physical process about conductor C, Fig. 7, as the

potential goes through a cycle. The conductor C begins with a negative potential which increases, decreases, and becomes positive. During the negative phase, the negative ions move outward along the lines of force towards B. If the conductors are sufficiently far apart, these ions will not reach B before the phase changes and they are again drawn toward C. However, if the spacing d is small enough, some of the n_0 ions will have reached B and so will have disappeared. That is, at a certain critical spacing n_0 will begin to decrease, and the coronal surface gradient will begin to increase.

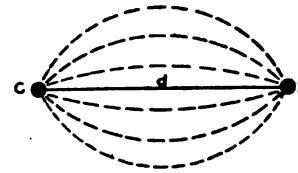

FIG. 7

This increase in X_s is shown by several curves in Peek's paper. The critical spacing at which this increase in X_s takes place is given in the following table (d observed).

a	X_s	d (observed)	$d = c\sqrt{X_s a}$
0.103	58,000	17 to 18 cm.	17.5
0.162	52,500	18 to 21	21.
0.2	50,000	21 to 23	23.
0.327	46,000	28 to 31	28.
0.412	44,000	32 to 34	32.

$c = 0.23$ = a constant.

The change in the gradient as the spacing is decreased is so gradual that the critical spacing d at which X_s begins to be increased cannot be sharply fixed.

The expression in the fourth column of the table for the critical spacing is derived from the following considerations: This spacing is the distance that an ion would move out from conductor C in a quarter-cycle. All of those ions that are to cross the surface X_0 at the crest of the positive wave, must be within such distance of the wire, that they can return while the potential is increasing from zero to a maximum on the positive phase.

Let k be the specific velocity of an ion, and X the gradient at a point x at a time t. Then $k X$ will be the velocity at that point and time.

$$\frac{dx}{dt} = k X$$

and
$$X = X_s' \frac{a}{x}$$

Also

X_s' varies with the time.

$$X_s' = X_s \sin p\, t$$

$$\frac{dx}{dt} = k\, X_s \frac{a}{x} \sin p\, t$$

$$\int_a^d x\, dx = k\, X_s \frac{a}{x} \int_0^{\frac{T}{4}} \sin pt\, dt$$

$$d^2 - a^2 = \frac{k\, X_s\, a}{\pi f}$$

Since a is very small compared to d, it may be neglected, and setting

$$c = \sqrt{\frac{k}{\pi f}} = \text{a constant}$$

the above becomes

$$d = c \sqrt{X_s a} \qquad (18)$$

which is the equation by which the fourth column of the table is calculated.

The Nature of the n_0 Ions

The theory here proposed for the corona is founded upon the assumption that there is a large number of ions n_0 which cross the surface X_0 and build up the ionization to n ions at the surface of the wire, while the gradient is near its maximum on the positive phase.

This foundation principle seems to be opposed by some experiments of Dr. Whitehead[6]. This contradiction, however, is only apparent. It is perhaps worth while to give his work in more detail and show that this is the case.

(a) An effect was sought for by increasing the original ionization about the wire by ionizing the air about the wire within

6. Trans. A. I. E. E., Vol. XXXI, 1912.

the cylinder by Röntgen rays. The result was negative; no change in the coronal voltage was observed.

(b) The wire is surrounded by thin paper tubes within the cylinder. "A clean copper wire 0.157 cm. in diameter, started the corona at 58.5 primary volts. This wire was then successively enclosed in thin paper tubes 2.54 cm., 1.27 cm. and 0.95 cm. in diameter. These tubes were slightly longer than the outer cylinder and were insulated and held accurately concentric by means of three threads at each end".

"Ions in the region outside of these tubes would be prevented from reaching the wire, and if these ions have any influence on the coronal voltage, we should expect an elevation of this voltage, when the wire is screened as above. No change in the coronal voltage was observed when the larger tube was in place. In the case of the smaller tubes the coronal voltage (primary) was lower, by 1.5 to 2 volts, than when the tubes were not inserted. In this experiment, the number of ions in the neighborhood of the wire is lower when the paper tube is in place."

A closer examination of the physical process about the wire will show, however, that neither the Röntgen rays nor the paper tubes can have much effect on the number of the n_0 ions considered in this theory.

Suppose that the alternating potential applied to the wire for experiment (a) is such that the surface gradient will just produce the corona.

For the sake of clearness, consider that the potential is applied to the wire at the beginning of the positive phase. The ions present, due to the natural ionization of the air, move inward toward the wire, and designate by N_0 those that cross the surface X_0 at crest of positive phase. These produce ionization by impact and N_1 ions arrive at the wire, (see Fig. 8). These N_1 ions are not numerous enough, however, to produce a visible corona. Some of these N ions are neutralized by the wire (current loss), and on the next phase, when the wire is negative, the remainder move outward, passing the positive ions which are moving inward. Many disappear by recombination during this time, but a number much greater than the original N_0 is left. On the next change to the positive phase, N_{01} ions cross the surface X_0 at crest of wave. These produce N_2 ions which arrive at the surface of the wire. Part of these ions disappear as before, but leave N_{02} ions for the next process. Thus the ionization builds up in a manner graph-

ically shown in Fig. 8. The n_0 ions of the theory and of Fig. 8 are many thousand times more numerous than the original N_0 which are due to the natural ionization of the air.

The Röntgen rays as applied by Dr. Whitehead would increase the N_0 ions, but not the n_0 ions. But the number of cycles required to build up the ionization would be decreased by the application of the Röntgen rays.

This process requires that a number of cycles should elapse between the application of the potential to the wire and the appearance of the corona. I venture to predict that such delay would be observed if the experiment were performed in the following way. The potential of the secondary should be adjusted so as

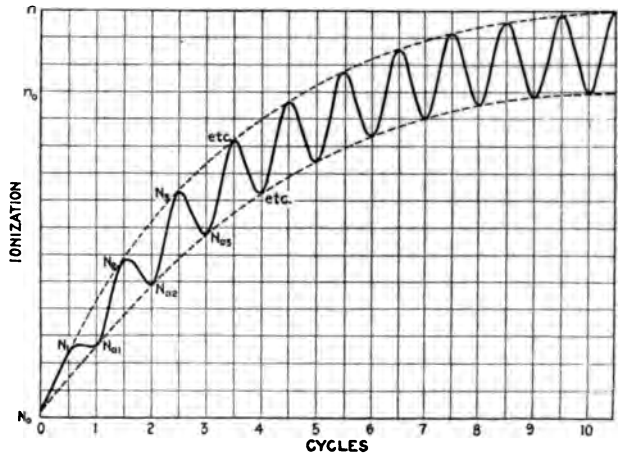

FIG. 8

just to produce the corona. A suitable switch should be placed in the secondary circuit. The current in the primary should be kept on continuously. The coronal discharge should appear many cycles after the closing of the switch in the secondary. This arrangement avoids the sudden rush of current into the transformer on closing the primary switch.

Such an effect has been observed. A graduate student, working under the direction of the writer at the Physical Laboratories of Columbia University, obtained such nice adjustment of potential difference that the discharge would regularly appear three minutes after the application of the potential to the electrodes. Here, the rate of production only slightly exceeded the

rate of disappearance of the ions. It took a long while to build up from N_0 to n ions.

The above view of the physical process about the wire also explains the absence of any considerable effects when the wire is inclosed in a paper tube. The building-up process at successive cycles indicated in Fig. 8, goes on inside the paper tube. As the wire is on successive negative phases, the N_{01}, N_{02}, N_{03} etc. ions are driven outward and cling to the inside wall of the paper tube. As the wire changes to the successive positive phases, these N_{01}, N_{02}, N_{03} ions come free from the wall of the tube, and move inward, producing ionization by impact in the same way as though the paper tube had not been there.

The negative ions while on the inner wall of the tube will not produce any disturbance in the electrical intensity about the wire, because of the law that there is no electrical force inside of a hollow conductor due to a charge on its surface. The paper tube experiment, which at first sight appears conclusive, really leaves the effect of the original ionization on the discharge still undetermined.

The laws governing the formation of the corona are thus fully explained by the known principles of the motion of ions and ionization by impact. The real dielectric strength of air is not altered by the curvature of the conductor. The apparent dielectric strength, however, is altered.

There is still an important problem in connection with the discharge, not considered in this paper. There is a loss of energy from the conductor, which increases very rapidly as the potential is increased beyond that required to produce the corona. It would be desirable to develop a theory that would completely describe this energy loss in terms of ionization by impact. However, new and great difficulties are encountered when this is attempted. The redistribution of the ions causes a modification of the electric field about the conductor. The representation of this new field distribution in terms of the ionic charges and their motions, by a differential equation, is a matter of very great difficulty.

DISCUSSION ON "THEORY OF THE CORONA" (DAVIS), WASHINGTON, D. C., APRIL 25, 1914.

J. B. Whitehead (by letter): Professor Davis's paper is noteworthy as being the first thorough-going attempt to explain the phenomena of corona formation in terms of the theory of ionization. In each of the papers of my series on *The Electric Strength of Air*, I have stated my opinion that the phenomena in question would ultimately be explained in terms of that theory. Professor Davis is the first, however, to offer to the Institute a theory which begins from the fundamental relations given by Professor J. S. Townsend, the originator of the theory of ionization by collision, as the explanation of all electric discharges in gases. Professor Davis makes a number of assumptions which will require careful investigation before acceptance. Among these is that which states as the critical condition for corona formation that the density of ionization at the surface of the wire should reach a constant value. In the process leading up to the arrival at this value he assumes a continuous generation of new ions by collision, beginning a certain distance from the wire and accumulating in time through successive cycles of the alternating electric intensity. If this is true, should there not be evidence of ionization for values of voltage just short of the corona-forming value? Our experiments have indicated no such preliminary ionization.

I should like to ask the origin of Professor Davis's figure of 26,000 volts per cm. as the value of X_0.

The correctness of the development of Professor Davis's theory depends largely on the value of α as given in formula (7). It would be interesting to know what other evidence there is in support of this value.

Professor Davis has evidently given careful thought and study to the relation of his theory to the results which have been presented in papers to the Institute. Indeed, the agreement between the theory and observations is so remarkable that it is to be hoped that Professor Davis will in a further paper discuss the possible errors introduced by several assumptions which he has made in the reasoning. I have not found it possible to check them all.

It may be well to point out that Professor Townsend has himself offered an explanation of the relation obtaining between the critical corona intensity, the diameter of the wire and the density of the gas, in an article in the London *Electrician* for June 6, 1913.

Harris J. Ryan (by letter): The Davis theory of corona presents for the first time a definite and satisfactory correlation of the essential factors that cause corona formation on high-voltage transmission lines. The theory has not been extended, as yet, so as to account fully for *local corona* that generally precedes full corona formation, and for the strength of the corona-formed

ionic (in phase) current in relation to frequency and voltage. This does not lessen its integrity nor its value. Merely its opportunity for growth is thus emphasized and such growth will be sturdy. In due course of time it will be extended so as to account for most if not all of the corona phenomena.

The author's fundamental assumptions in regard to the dual origin of the n_0 ions and the corona-culminating role of the n ions are made upon firm ground. Assumptions employed in the construction of a satisfactory theory must be nominated by corresponding facts. The Columbia University experiment which demonstrated the time-lag of the arrival of the initial corona has contributed an important nominating fact in regard to the n_0 ions. We have found in our own work that the normal critical visual corona-forming voltage applied to parallel wires may be lowered greatly, as much as fifty per cent, by liberating near such wires an independent supply of ions. This was done by mounting a fine wire between the high-voltage wires and charging it from a static machine. Objection to this experiment was made on the ground that the electric field about the high-voltage wires is increased by the presence of the charged fine wire. So it is, but the increase is far too little to account for the results. This has been demonstrated by computation and experiment. The results of the experiment fortify the author's assumptions that corona formation is dependent upon the initial supply of free ions, N_0, and " that the discharge will appear when the ionization per unit area at the surface reaches a certain constant value, n." Also that " the density of ionization at the surface of the conductor will increase somewhat without ionization by impact as the N_0 ions move inward."

We have been working during the past two years with a steady, undamped, high-frequency, high-voltage source and have observed that coronas formed at 60,000 cycles per second consume large amounts of power and develop correspondingly high temperatures. These corona temperature effects continue to increase with frequency increase. The highest frequency used has been 600,000 cycles. The values of such steady high-frequency high voltages required to discharge across sphere gaps are much the same as the corresponding values at low frequencies. The corresponding voltages required to discharge through corona-forming blunt-pointed gaps are generally about one-half those required at low frequencies. Large, vigorous, local high-frequency corona brushes are formed on slight provocation at abnormally low voltages. A brush of this character may be blown by lung power from the point of the circuit where it originated to another point whereat it could not be started by the unaided action of the circuit supplied by a given voltage. These corona brushes may also be started at sub-critical voltages by touching the circuit momentarily with a stick of wood. The corona brush will start at the spot on the conductor touched by the wood. In these high-frequency phenomena we have much evidence of

the correctness of the author's implied assumption that the number of ions maintained in action, producing in-phase current, depends upon the shortness of their amplitudes of actual travel and of intervals of replenishment, *i.e.*, upon the frequency of the source.

Edward Bennett (by letter): The paper on the *Theory of Corona* contains a derivation from rational considerations of an equation which fits certain curves experimentally determined by Peek, Whitehead and others. These curves show the relation between the radius of wires of different diameters and the hypothetical gradients at the surface of the wires which cause ionization of the surrounding air to become evident.

The justification for some of the rational notions made use of by the author is not at all clear to me, while other assumptions do not seem to be in accord with the interpretation to be placed upon the experimental data. For example, it seems to be assumed that ionization will first be evident during that half-cycle of the alternating wave in which the electrons are moving inward across the surface Q of Fig. 1 toward the surface of the wire. Now, oscillograms taken at air pressures in the neighborhood of one cm. of mercury show that as one gradually raises the voltage between wire and surrounding cylinder, there is quite a range in voltage during which copious ionization occurs only during the half-cycle in which the wire is cathode, or the electrons move outward. At atmospheric pressure it is impossible to tell from the oscillograms the polarities under which copious ionization sets in. That is, as one slowly raises the voltage between the wire and surrounding cylinder the oscillograph gives evidence of ionization at substantially the same impressed voltage at which the eye sees the bluish haze around the wire. In addition the oscillograph also shows that ionization is occurring not only during the half-cycle in which the wire is positive but also during the half-cycle in which the wire is negative to the cylinder. This would seem to indicate that ionization resulting from both positive and negative ions should receive consideration in any derivation of the relation between the critical gradient and the radius of the conductor.

Referring to equations (**5**) and (**6**) the author makes the statement: "An inspection of Fig. 1 will show that the number of n_0 ions, crossing the surface Q per unit area, varies inversely as b; consequently, we may approximately assume that the whole term on the left is a constant for first appearance of discharge." It is not clear to me either why n_0 varies inversely as b, or why the left member of equation (**6**) may be regarded as approximately constant, and it would be gratifying if the author would elaborate on these two assumptions.

Alex. Chernyshoff (by letter): Mr. Davis and Prof. Townsend in their work have taken into account only the kinetic energy of the electrons and positive ions, leaving entirely out of consideration the possibility of the influence of the electric field on the

The first member will gain more and more in significance as the diameter of the cylinder increases.

When the potential is alternating or variable the phenomena will be very much more complicated and it will not be possible to integrate the differential equation and in this way determine fundamental dependence of the gradient from the diameter of the cylinder and the constant of ionization, but this increased complexity of the phenomena does not change their essential character. I therefore think that when the distance between the earth and the conductor is considerable the variation of the field distribution of potential from the logarithmic curve will be considerable. In the case of ionization through collision there will be an enhanced inequality in the distribution of free electricity due to the difference in mobility of various ions.

In conclusion I want to relate one very interesting experiment demonstrating the action of light on electric discharges. Lebedinsky proved that light can not only facilitate the appearance of an electric discharge in the shape of a spark between electrodes, but that under certain conditions it may check its appearance. The experiment was conducted as follows:

A variable tension was placed near the breakdown. A slight illumination of one of the unsymmetrical electrodes regularly produced the appearance of a spark discharge. When the illumination was strengthened, irregular discharges were produced, and with a stronger illumination the discharges were discontinued entirely, while there was no change in the tension between electrodes. The reason for this phenomenon is the increased number of negative ions changing the distribution of potential in such a way as to prevent a discharge. This phenomenon, viewed from our point, demonstrates the importance of the field distribution and the dependence of the distribution of the free ions in the gas.

F. W. Peek, Jr. (by letter): It may be of interest to state, in a brief way, the manner in which our law of visual corona was derived, and also to call attention to the fact that it is a rational law. In 1910 I conducted an investigation, very carefully determining the visual corona voltages of various sizes of polished parallel wires at various spacings. This was given in my paper before the A.I.E.E. in June, 1911. For any conductor the voltage gradient at rupture, g_v, was found to be constant, independent of the spacing (except at very small spacings), but increased very rapidly as the radius of the conductor was decreased. Thus air *apparently* had a greater strength for small conductors than large ones. This was formerly pointed out by Professor Ryan. The experimental data curve between g_v and radius r was found to be regular and continuous. A number of equations could readily be written which would fit these data. It was desired, however, to establish or build up a rational equation. The old idea of air films at the surface of the conductors was abandoned, after tests with very light (aluminum)and very heavy (tungsten)

metals showed that the density of the metal of the conductor had no influence on g_v, which should be the case if the difference were caused by air films, as the air film should vary with the density of the conductor.

A rational law of visual corona was deduced from the data, reasoning as follows:

Energy of some form—be this the $\sum \frac{m v^2}{2}$ of the energy of the moving ions, or whatever form it may—is necessary to rupture insulation. This is borne out by experiment with transients, which show that finite time is necessary to rupture insulation, and that if this time be limited the voltage must be increased to accomplish the same results in the limited time. Heating results at rupture, etc. These facts imply definite finite energy. The gradient or stress to rupture air in bulk in a uniform field, g_0, should be constant for a given air density or molecular spacing. In a non-uniform field, as that around a wire, the breakdown strength of air, g_0, is first reached at the conductor surface; at a small distance from the conductor surface the stress is still below the rupturing gradient. Hence, in order to store the necessary finite rupturing energy the gradient at the conductor surface must be increased to g_v, so that at a finite distance away the gradient is g_0. This means that a finite thickness of the insulation must be under a stress of g_0 or over. The rupturing energy is in the zone between g_v and g_0. The thickness of the zone should be a function of the conductor radius. It was found that at $0.301 \sqrt{r}$ cm. from the conductor surface the gradient at rupture is always constant and 30 kv./cm. (at standard air density). The relation between g_v and r may now be directly expressed by the simple law

$$g_v = g_0\left(1 + \frac{0.301}{\sqrt{r}}\right) = 30\left(1 + \frac{0.301}{\sqrt{r}}\right)$$

For parallel planes or for air in bulk

$$r = \infty$$
$$g_v = g_0.$$

Thus the strength of air is constant and equal to 30 kv./cm., but in non-uniform fields is apparently stronger, as explained above. If the air is made less dense, that is, if the molecular spacing is changed, the strength of air in a uniform field should decrease directly with the air density.

$$g'_0 = \delta g_0$$

However, for non-uniform fields, the energy distance should also change thus

$$0.301\, r\phi\ (\delta)$$

I found this to be borne out by experiment and the complete equation containing air density correction to take the simple rational form

$$g_v = g_0 \delta \left(1 + \frac{0.301}{\sqrt{\delta r}}\right)$$

If the energy distance is limited to less than $0.301 \sqrt{r}$ the apparent gradient should increase. This also is borne out by experiment, as shown in later papers.* The visual tests on various forms of electrodes—as spheres, wires, planes, etc.—as well as loss measurements, all point to an energy storage distance and a constant strength of air of 30 kv./cm.

At *continuous* high *frequency* where the rate of energy, or the power, is great, frequency *may enter* into the energy distance, thus

$$0.301 \frac{r}{\delta} \phi (f)$$

and spark-over take place at lower voltages. Where the time is limited, as in an impulse of steep wave front, a much higher voltage should be required to start arc-over. This is also borne out by experiment.

Thus far, I have said nothing in regard to the form of this rupturing energy. Such speculation was not necessary in order to develop a rational working equation. After a law is developed it is interesting and instructive to fit speculative theory to that law.

In the discussion of my paper, *The Law of Corona*, 1911, Dr. Steinmetz suggested how the theory of ionization by collision could be made to fit the law of corona which had just been brought out. This suggested application is the same as that followed by Mr. Davis in his mathematical work, and is found on pages 1968, 1969 of the A.I.E.E. TRANSACTIONS for 1911. The theory that initial ionization could not affect the starting voltage is brought out on page 1122 of the A.I.E.E. TRANSACTIONS for 1912. I have also suggested the same application of the electron theory in my papers of 1912 and 1913, and also in discussions. Briefly, the rupturing energy may be the $\sum \frac{m v^2}{2}$ of all the ions necessary to produce ionic saturation, and hence conduction or corona.

When low potential is applied between two conductors any free ions are set in motion. As the potential, and, therefore, the

*See *The Law of Corona and the Dielectric Strength of Air*-II, (Peek), TRANS. A. I. E. E., 1912, XXXI, I, page 1051; and *The Law of Corona*-III, TRANS. A. I. E. E., Vol. XXXII, 1913, p. 1767.

field intensity or gradient, is increased, the velocity of the ions increases. At a gradient of $g_0 = 30$ kv./cm. ($\delta = 1$) the velocity of the ions becomes sufficiently great over the mean free path to form other ions by collision. This gradient is constant and is called the dielectric strength of air. When ionic saturation is reached at any point the air becomes conducting and glows, or there is corona or spark.

Applying this to parallel wires—when a gradient, g_v, is reached at the wire surface any free ions are accelerated and produce other ions by collision with molecules, which are in turn accelerated. The ionic density is thus increased by successive collisions until at $0.301\sqrt{r}$ cm. from the wire surface, where $g_0 = 30$, ionic saturation is reached, or corona starts. The distance $0.301\sqrt{r}$ cm. is, of course, many times greater than the mean free path of the ion, and many collisions must take place in this distance. Thus, for the wire, corona cannot form when the gradient of g_0 is reached at the surface, as at any distance from the surface the gradient is less than g_0; a finite thickness of air must be under a stress equal to or greater than g_0. The gradient at the surface must therefore be increased to g_v so that the gradient a finite distance away from the surface ($0.301\sqrt{r}$ cm.) is g_0. That is to say, energy is necessary to start corona, as outlined above. g_0 the strength of air, should vary with δ; g_v, however, cannot vary directly with δ, because with the greater mean free path of the ion at lower air densities, a greater "accelerating" or energy distance is necessary. In the equation $a = 0.301\sqrt{\frac{r}{\delta}}$; that is, a increases with decreasing δ.

When the conductors are placed so close together that the free accelerating or energy distance is interfered with, the gradient g_v must be increased in order that ionic saturation may be reached in this limited distance.

Initial ionization of the air cannot affect the starting voltage, since such ionization must necessarily be very small compared to the residual ionization after each cycle. When, however, the initial ionization is very small when voltage is first applied, an appreciable time is necessary before corona starts. The starting voltage, however, is not affected for continuously applied a-c. or d-c. voltage. For transients of short duration, or for single impulse, much higher voltage should be required to produce the same results in limited time—that is, higher impulse voltages should be required to cause corona or spark-over.

Mr. Davis has mathematically connected the theory of ionization by collision with the law of corona already established. His results seem to indicate in a very interesting way that the rupturing energy may be the $\sum \frac{m v^2}{2}$ of the energy of the colliding ions. Of course this does not definitely prove this particular applica-

tion of the ionization theory. It shows that by a proper valuation of the constants, his equation will coincide with the established experimental equation. A number of equations might apply in the same way. It is interesting to quote as follows from his paper:

"The fact that equations (**14**) and (**15**) plot into almost identical curves is evidence that the theoretical equations express law of corona as accurately as the empirical equations."

The ionization theory will be more fully established for practical application when we may reverse this statement, or when theory so reaches the stage that we may say, "it is remarkable that the practical results so well check the theoretical ones."

Mr. Davis is to be congratulated upon the important work which he has done in actually applying theory to obtain practical working results. The electron theory has not been so definitely applied before to obtain practical results, but only vaguely and in a speculative way, fitting the theory to suit the particular case. It is such important work that will bring forward and extend this theory.

Bergen Davis (by letter): The discussions of my paper on the "Theory of the Corona" have interested me, and I appreciate the criticisms and suggestions which the various gentlemen have made. It is perhaps not necessary to take time and space for a lengthy reply, but I will consider a few points that seem to need further explanation.

(1) Professor Whitehead inquires why a constant density n of ions per unit area is assumed as a criterion for the appearance of the discharge. This is a natural assumption. The ionization progresses with the voltage according to a high exponential law. The rate of increase with the applied voltage is definite and can be experimentally reproduced at will. This refers to experiments with steady potentials applied to plate electrodes. The phenomenon is progressive until it becomes visible, and the ionization at *first* visibility is undoubtedly constant, at least for the same observer. This rapid rise of the ionization with the voltage has been found by all experimenters, and I would refer the reader to the numerous papers on this subject published during the last decade by Professor Townsend and his fellow workers. Professor Whitehead should have detected this partial ionization had his conditions been steady enough, and his detecting instruments of sufficient sensibility.

The origin of the constant $x_0 = 26{,}600$ volts per cm. is explained in the original paper. It was necessary to find an integrable equation that would agree with the theoretical expression (**7**) for the relation between α, p and x. This integral equation is

$$\frac{\alpha}{p} = A + B\left(\frac{x}{p} - 350\right)^2$$

The number 350 is a constant, and on eliminating p from the

parenthesis, when p is expressed in centimeters of mercury, one obtains $76 \times 350 = 26{,}600$ for the value of x_0 at normal pressure.

The physical meaning of the constant x_0 is that ionization by impact will occur at all gradients greater than 26,600 volts per cm. and that one may neglect all ionization at gradients below that value. As a matter of fact, the kinetic theory of gases shows that some ionization by impact may occur at any gradient, however small.

Professor Whitehead also questions the experimental basis of the theoretical equation (7). Since the publication of the paper on the corona, I have compared equation (7) with all the experimental results obtainable for the relations between α, p and x. If one takes $v = 11.5$ volts, and the mean free path of an electron to be eight times that of a molecule, then equation (7) agrees with the experimental results with an accuracy of five per cent or better. The validity of this equation is thus supported by all of the experimental work on ionization by impact.

(2) The points made by Professor Bennett. It is not assumed that ionization will first be evident at that half-cycle in which the electrons move towards the wire. Ionization by impact occurs when the electrons move outward as well as inward, but the *first* appearance of the visible corona will occur when the wire is on the positive phase. After the discharge is established, the ionization is very copious, and it probably occurs on both phases. That the discharge will occur when the wire is on the positive phase, is shown by the experiments of Prof. Townsend, (*Phil. Mag.*, April, 1914) who finds that for all pressures greater than 5 to 8 cm. of mercury, the discharge occurs at a less gradient for wire positive than when it is negative. The contrary is the case for smaller pressures. This theory is applied only at pressures greater than 5 cm. mercury. Professor Bennett's own experiments were made at 1 cm. pressure. He finds in this case that the discharge first occurs when the wire is negative. This also was observed by Professor Townsend. No matter whether the discharge occurs when the wire is positive or negative, the greater part of the ionization by impact is due to the negative ions.

Professor Bennett also has difficulty with the constancy of the left member of equation (6). The n_0 ions crossing Q inward are concentrated by the curvature. The geometry of the figure will show that the density of ionization will increase as the n_0 ions move inward without ionization by impact. The numbers n and n_0 refer always to the number crossing unit area. Now if the total number of ions outside of Q is constant, then it is evident that the number n_0 crossing the surface Q will be less as b is larger. The surface of a cylinder is directly proportional to its radius.

The concentration due to curvature will be as b to a, and the value of n_0 will be inversely as b for any given case. That is, one is justified in assuming $\left(\frac{n}{n_0} \cdot \frac{b}{a}\right)$ to be approximately constant.

Presented at the 295th Meeting of the American Institute of Electrical Engineers, New York, May 19, 1914. Under the auspices of the Committee on Use of Electricity in Marine Work.

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ELECTRICITY THE FUTURE POWER FOR STEERING VESSELS

BY H. L. HIBBARD

ABSTRACT OF PAPER

Electrical development in the marine field has been confined in a large measure to the navy, and the best experience with electric steering gears has been obtained from navy installations.

Up to the present time steam has been the universal power for operating steering gears, but certain disadvantages are inherent in this system which can be overcome by the electric drive, and additional advantages obtained. The history of electric gears shows that many different schemes have been tried and proved failures owing to faulty designs and imperfectly developed apparatus. At present several different systems are in successful operation.

To obtain full benefit of the advantages possible from an electric drive, much depends on the selection of apparatus with characteristics best suited to the work. The problem of electric drive is largely one of control. The calculations for rudder and motor horse powers must be carefully made, with the proper assumptions for the conditions presented.

Several installations in the navy have shown excellent results; in the case of the battleship *Texas* the data obtained show preliminary calculations were quite accurate. Results obtained seem to justify the prediction that electric steering gears will be used quite generally in the future.

THE MARINE field has probably been one of the most backward in the adoption and development of electrical apparatus owing, in part, to natural causes, such as high first cost of electrical over steam machinery, the long familiarity aboard ship with steam machinery, and the somewhat higher order of care and inspection required for electrical apparatus; but in the main we believe it has been due to the traditional conservatism of the seafaring man and his reluctance to try something new when that which has been used before seemed to answer the purpose, owing in a large measure, doubtless, to his belief that this policy insured the greatest protection to the lives and property under his care. The most conspicuous exception to this, however, has been the American navy, which is not only a larger user of electrical machinery than the merchant marine, but also leads the navies of the world in this respect.

During the last few years, however, considerable attention has been given to the development of electricity on board ship, and to many of the auxiliaries we have seen its application, as well as to the electric propulsion of ships, which is now also being given careful consideration. One of the auxiliaries of the greatest importance to the operation of the ship and which also involves some of the most interesting engineering problems, to which electric power and control is now being applied, is the electric steering gear. In line with our previous statement, however, the greatest use of electricity for this purpose has been in the navy, and, therefore, our future statements will refer in a large measure to naval installations of electric steering gears.

The Steam Steering Gear

Large steamers of the present day are fitted with either the ordinary form of rudder or with a balanced rudder, battleships being almost invariably fitted with the balanced type in order that they may maneuver more quickly. Fig. 1 illustrates the general arrangement of a steering gear controlled by a steam engine on a warship, operating a partially balanced rudder.

Practically all steamers except those of the smallest size at the present time make use of steam power for moving the rudder, and in addition to this power drive, most equipments include provision for steering by hand either through handwheels, geared to the steering gear, or by block and tackle to the tiller. The possibility of accident to the prime mover and the importance of avoiding a complete breakdown renders the addition of the manual drive necessary, although the rate of turning with the hand gear is, of course, much slower than with power.

The successful introduction of steam power for operating the rudder was made about 1866, by McFarlan Grey. A steam gear designed by him was placed on the *Great Eastern* and the ease with which steering could be done under the new power as contrasted with the old hand method, led to its rapid adoption on all classes of steamers. Improvements have, of course, been made in details, better engines being now made than formerly and better control of them obtained, but, nevertheless, the present steam equipment does not vary greatly from the first one installed.

The control of the valve of the steam engine from the bridge has been accomplished in various ways, in some cases by direct shafting and gears from the steering wheel, in others by wire

rope transmissions called tiller ropes, and in other installations, particularly of large capacity, by hydraulic telemotors. In practically all cases, however, the control has been by what has been known as the follow-up system, in which the arrangement of valve gear is such that the steam is cut off and the rudder

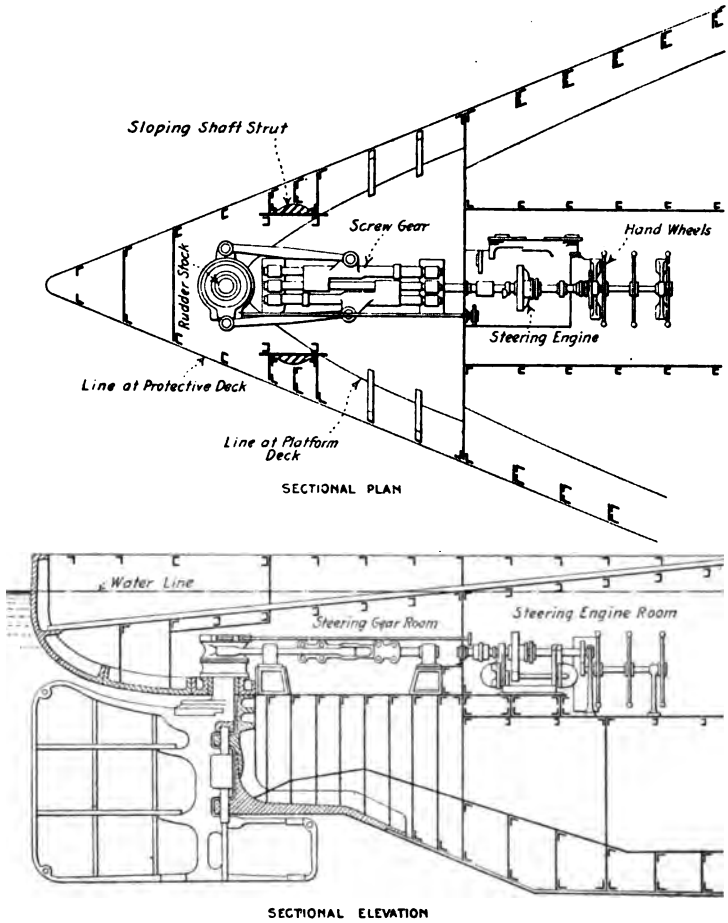

FIG. 1—STEERING ARRANGEMENT OF A WARSHIP OPERATING A PARTIALLY BALANCED RUDDER

stopped at the angle corresponding to the position at which the helmsman has set his steering wheel. With this arrangement the helmsman turns his wheel to the angle desired as shown by the indicator on the steering stand, and without further operation of the wheel the rudder moves to this point and is automatically

stopped. This system of control, we believe, has been used in practically all classes of vessels, with the possible exception of some large river steamers, and has been so generally used for many years as to be, in the mind of the mariner, an integral part of a steering mechanism.

Notwithstanding the general popularity of the steam drive and the excellent service which it has performed for years on thousands of vessels, there are certain disadvantages which are inherent in the system, some of which are as follows:

1. With the boilers near the center of the ship and with the steering engine usually at the stern or in some cases way forward, long and expensive lines of steam piping are required, and a careful design for the leads of piping must be made in order to clear stowage in store rooms, ammunition or other spaces through which they must run. They must be well insulated to avoid heavy condensation losses in the steam, as well as to reduce as much as possible the rise in temperature of spaces, especially powder magazines on war vessels. Even the weight of the piping, lagging, bulkhead fittings, etc., is often a considerable item, and in the case of a battleship this will amount to about three tons, being equal to about 45 per cent of the weight of the steering engine itself.

2. Considerable steam is wasted due to valve setting, it being common practise to set the valves of the steam engine so that even when the rudder is at rest a considerable amount of steam is blowing through the engine. The steam steering engine usually takes steam full stroke and for this and other reasons is an exceedingly inefficient mechanism.

3. The engine must be designed to do the maximum work required of it, that is, all parts of the engine must be of sufficient size and strength to develop the power required at the maximum rudder angle, which is reached but very infrequently in ordinary steering. The engine does not lend itself to overloads as does an electric motor, which point is of the greatest importance and will be given special consideration later.

4. The steam engine is provided with reciprocating parts which are subject to severe stresses when the engine speeds up due to sudden decrease of load on the rudder as it is moved back to a central position. These reciprocating parts do not produce a uniform torque, as in the case of a rotating armature, and they furthermore are the source of considerable vibration in the operation of the gear. When in harbors the steam engine

requires turning over at rather frequent intervals to prevent piston, cylinders, etc., from becoming rusty.

5. The mechanical connections from the bridge to the engine valve are a considerable source of trouble, and wire rope leads frequently wear out. The necessity of running these mechanical connections through compartments and watertight bulkheads is the source of difficulties in the construction of the ship, and in the case of wire ropes, there must be continual care exercised to keep the tubes through which they pass filled with grease, reducing the friction wear to a minimum. If these mechanical parts are not kept in excellent condition the friction causes the steering wheel to be operated with considerable effort and breakage of these parts has not been an uncommon occurrence.

Results to be Accomplished by the Use of Electric Drive

With the electric gear it is not only possible to overcome, at least in a great measure, the disadvantages enumerated above for the steam engine, but it is also possible to obtain a flexibility, simplicity and accuracy of control not permissible with the steam gear. The results to be accomplished by the installation of the electric steering gears are, therefore:

1. The reduction of the weight and space occupied by the driving mechanism;
2. The suppression of heat in the spaces adjacent to the gear;
3. The elimination of accidents which may occur in the bursting of steam pipes;
4. The reduction of vibration and noise and increase in habitability, due to these factors;
5. The obtaining of a mechanism very much more efficient in its operation than the steam equipments;
6. The simplification of the means of controlling the mechanism from the bridge, with increase in the ease of operation for the helmsman;
7. The increase in rapidity and accuracy of response of the rudder to the movements of the controlling mechanism.

History of Electric Gears

The subject of electric steering gears has been given some attention by engineers for the past 15 or 20 years, but within recent years only has the matter been given sufficient attention or the electrical apparatus developed to such a point as to per-

mit of successful results being attained. Several electric steering gears of different types have been tried in foreign navies, but it is not known whether any of them have proved completely satisfactory. In a great many cases after being thoroughly tried out they have been stripped and the steam gear again used, some doubtless being defective in design and some in the perfection of details, but others failed due in a large measure to flaws in the controlling apparatus.

At the present time motors and controlling appliances have been developed to such a point as to permit readily of the solution of the problems involved and also to render their performance reliable and trustworthy. The main feature in the electric steering gear has, however, become one of control, and too much emphasis cannot be laid on this point. This problem of control has been attacked by several radically different schemes, the principal ones being outlined below.

Direct current is used universally on board ship, with pressures varying from 80 to 220 volts; the present standard in the American navy is 125 volts, with many of the older ships provided with 80-volt equipments, while in the German navy the voltage is 220, and the same is now being considered by the U. S. naval authorities and has recently been adopted on one of the latest battleships as a trial experiment. It is not necessary, furthermore, to give consideration to the use of alternating-current motors for operation of steering gears, this current not being employed to any extent on shipboard, and such motors would not give the varying torque and speed characteristics which are here especially desirable.

One of the earliest electric steering gear systems considered in this country was known as the Van Duzer-Mason system and was patented about 1893 and is described in the Proceedings of the U. S. Naval Institute of that year. This system contemplated the use of a motor direct-connected to the rudder mechanism and its operation controlled by a simple form of controlling device operated on the follow-up system, but so arranged as to follow up at only a limited number of definite angles of rudder travel, and produced, therefore, a very coarse control. It is not known on what vessels this scheme may have ever been tried.

Several systems involving the use of magnetic clutches between the motor and rudder gear and of differentially controlled mechanisms have been tried, but for various reasons have not proved successful.

One of the first successful electric steering gears is that designed by Mr. Mathias Pfatischer and known as the Platischer system. This gear was placed on eight of the Imperial Russian naval vessels, a number of which were destroyed or captured by the Japanese during the recent Russo-Japanese war. It was also installed on two large liners built in this country for the Pacific trade and has been in constant use since 1902 on the liner *Finland*. One equipment has also been installed by the U. S. Navy on the cruiser *Montgomery* and we understand its operation has been generally quite satisfactory.

This system generally employs a shunt motor for operating the rudder, which is controlled with the varying voltage system by a motor-generator set especially supplied for the purpose. The field of the generator or generator exciter is controlled from the steering stand at the bridge on the Wheatstone bridge principle, the bridge being formed by one rheostat located at and operated by the steering stand and the other located at and operated from the rudder crosshead. The unbalancing of the bridge rheostat by the movement of the wheel gives current to the generator field and therefore, voltage and current to the rudder motor. The balancing of the bridge again by the movement of the rudder crosshead cuts off current from the generator field and the motor is stopped, constituting an electric follow-up control.

Objections which may be offered to this system are the size, weight and cost of the motor-generator set, which, furthermore, is always in rotation even though the rudder is at rest, and the no-load current of this set is an appreciable amount, being as much as 25 to 30 amperes on sets as small as 25 h.p. With this type of follow-up also the available power of the rudder motor is proportional to the unbalancing of the Wheatstone bridge and approaches zero as the balanced position is reached, which is the point frequently where the maximum torque is desirable, and the result must be the installation of a motor larger than would otherwise be necessary.

Several years ago the Navy Department became interested in the question of steering its ships by electricity owing to the possibilities presented of effecting the economies outlined above for the electric gear. In about 1902 the Department devised a steering gear operated on the follow-up system, and purchased apparatus of different manufacturers to effect an installation on one of the small monitors which had been recently constructed.

The results obtained from this equipment were not satisfactory. The question, however, remained under discussion for a number of years until about 1909, when a contract was placed for supplying an electric steering gear for the cruiser *Des Moines* as an auxiliary to the steam engine outfit. For this purpose the use of an electric motor taking its power directly from the dynamo mains and operated by a powerful automatic controller, thus eliminating the necessity of a motor-generator outfit, was advocated. The contract specified that no payments should be made unless the gear proved itself satisfactory in service and in the event of its failure it was to be removed by the contractor at his expense. The contract further required the control of the motor to be similar to that of the steam engine, *i.e.*, the follow-up system must be employed, and to accomplish this a small follow-up drum controller was provided in the steering engine room and operated differentially by the ship's tiller rope from the wheel on the bridge and the motor driving shaft.

The preliminary trials of this arrangement of gear were quite successful, although the writer found upon going aboard the vessel before the trials, that the officers and crew were prejudiced against the electric gear and considered it an unwelcome visitor on their vessel. After the successful preliminary trials of the follow-up gear the prejudice was overcome and it was then suggested that a non-follow-up type of control would be much simpler and easier to operate, but the reply was made that officers and men had steered with the follow-up system for years and it was foolhardy to think of adopting any other type. After considerable persuasion, however, permission was granted to install on the bridge a small reversing switch controller operating the main controller through four small wires and thus entirely cutting out of the operation the steering wheel and the tiller rope connections. After about a month's trial of this system of control the first report to the Department states in effect that the quartermaster and helmsmen learned to steer by this new method in about five minutes and now much preferred it to the old wheel control. Steering by the non-follow-up system on this vessel, therefore, became the prevailing fashion.

Although the reports from the *Des Moines* were of a satisfactory nature, the Navy Department was still naturally doubtful about the use of electric steering equipments, especially as regards the elimination of the follow-up principle. It was decided, therefore, to install such a gear as this on the scout cruiser

Chester, to be operated only by the non-follow-up system, and remove the steam gear entirely in order that confirming opinions might be obtained of abandoning the time-honored follow-up control and of steering naval vessels by electricity. Contract was, therefore, placed for the installation of a similar equipment of 75 h.p. on the *Chester* as against the *Des Moines'* 40 h.p. equipment, and this installation was completed the early part of 1912, about two and one-half years after the first installation had been made on the *Des Moines*. The motor with disk brake for the *Chester's* equipment is shown in Fig. 2.

Since this time installations of the same type of gear of 150 h.p. capacity have been made on the battleships *New York* and *Texas*. A further description of these equipments and of many of the results obtained will be given later.

Other installations of electric steering gears have recently been effected by another manufacturer on the Argentine battleships *Rivadavia* and *Moreno*, which are just reaching completion at shipyards in this country. These equipments consist of a 150-h.p. motor, 400 to 600 rev. per min., operated with combined rheostatic and field control. The motor operates the rudder at a lower rate of speed than the steering gear engine, to which it is considered an auxiliary, the requirements being hard-over to hard-over in 40 sec. The motor in question is shown in Fig. 3.

The controller consists of a contactor panel provided with four reversing contactors, a dynamic brake contactor, five accelerating contactors and other small contactors for controlling the field strength and the electromechanical brake.

The master controller is driven by a differential gear in order to provide the follow-up feature. Transmission from the steering wheel to the steering room is accomplished by hydraulic telemotor or wire ropes that are used for the steam engine control. The steam valve may be disengaged by a clutch, and the part of the differential gear, which operates the controller, connected in place of it, and the other part of the differential gear is connected to the steering gear itself. When the controller is turned to a certain point by the steering wheel, the motor begins to turn and will continue to turn until the action of the differential gear, driven by the steering gear itself, turns the controller to the " off " position and stops the motor.

The first position of the controller closes the proper reversing contactors and the current passes through the armature and all of the starting rheostat. The first accelerating contactor then

closes, and after the motor has speeded up sufficiently the next contactor automatically closes, allowing the remaining three to follow quickly after each other, bringing the motor up to the speed corresponding to the full field strength. If the controller is turned further than this, one of the field contactors is opened and the field weakened; a little further motion of the controller opens the second field contactor, still further increasing the speed.

A limit switch, carried on the same shaft as the master controller cylinder, automatically strengthens the field of the motor when the rudder has been turned to a certain definite angle from the mid position, and at a greater angle the field is strengthened still more, bringing it up to its full field strength. This provides an increased torque per ampere when the rudder is a considerable angle from the mid-ship position.

As the rudder returns to the position for which the steering wheel is set, the controller is turned to the " off " position, and if the rudder should be inside of the limits of 10 deg. either side it will be running at full speed. Just before the " off " position is reached the field is strengthened by one contactor. This increase of field strength causes a current to flow from the motor armature into the line, exerting a dynamic braking effect and reducing the speed of the motor. A moment later the field is strengthened again with the same effect, so that at the instant the main contactors open and the motor is disconnected from the line, the speed has been considerably reduced. The dynamic brake is then applied by the action of the proper contactor and the electromechanical brake follows an instant later.

As is later shown, the use of a compound winding exerts a greater torque per ampere with heavy loads, but owing perhaps to the relatively high speed of the armature and the necessity of very accurate stopping with the follow-up control, it seems to have been considered advisable to produce a slowing down effect before the brakes were applied. For that reason a shunt field was used on these equipments, which can be strengthened just before disconnecting from the line. The motor is provided with a small amount of series field winding but it is essentially, in its characteristics, a shunt motor.

The limit switch, besides performing the function of strengthening the field at certain positions of the rudder, will also cut off the power at the end of its movement if it is not already cut off by the movement of the controller. An overload relay is provided, which re-inserts the starting resistance in the armature

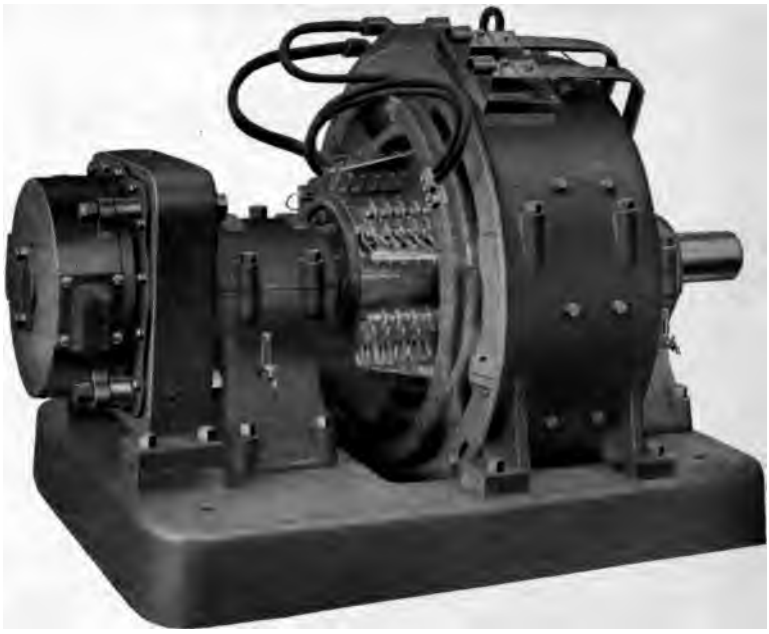

FIG. 2 [HIBBARD]

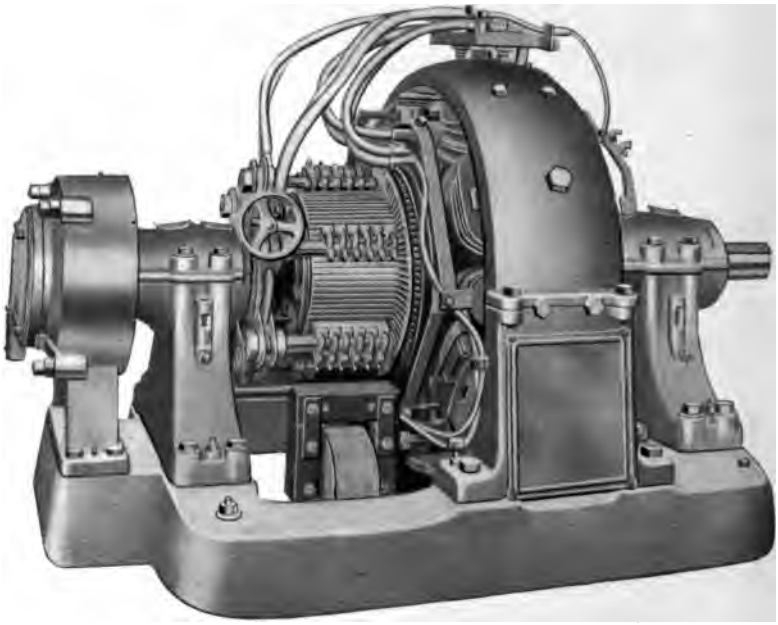

FIG. 3 [HIBBARD]

FIG. 5 [HIBBARD]

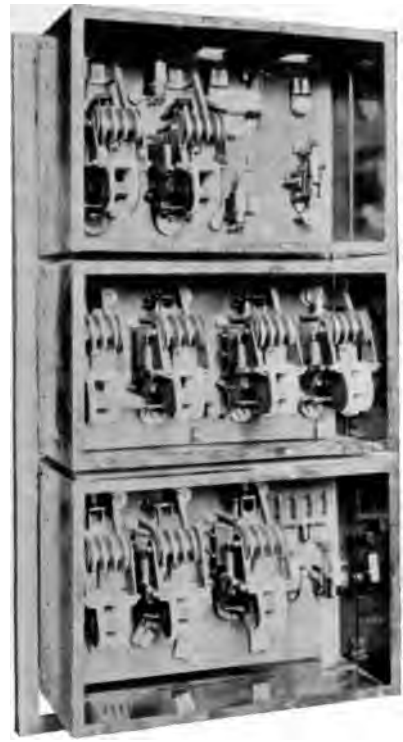

FIG. 6 [HIBBARD]

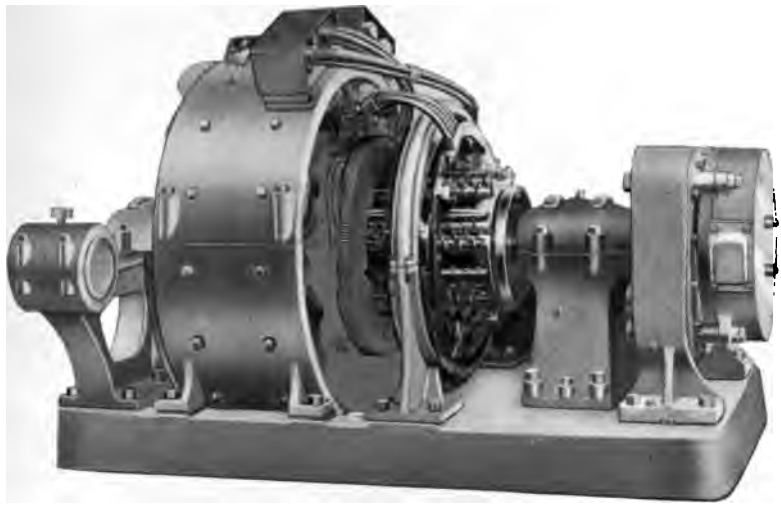

FIG. 8 [HIBBARD]

circuit in case of overload, instead of interrupting the circuit entirely.

We believe these equipments have not yet been tried out in service and we cannot, therefore, comment on results obtained.

The same company is also providing an electric steering gear for the American navy, which is to operate the rudder in the same time as required of the steam engine. The equipment consists of a rudder motor, motor-generator, switchboard, steering stands, selective switch and limit switch. The speed of the motor is controlled by varying the field strength of the generator according to the variable-voltage system and the system has no follow-up device. The motor is rated at 350 h.p. and when operating at rated voltage and full load, has a speed of 250 rev. per min.

The motor-generator is rated at 290 kw. output and runs at a speed of 1000 rev. per min. The motor has an accumulative compound winding and the generator a differential compound winding, so that the extreme overloads of voltage on the generator will be reduced both by reduction of speed and by the demagnetizing effect on the generator field; also the reduction of speed will deliver considerable energy for a few seconds to the generator circuit. The motor of the set is wound for 120 volts to agree with the ship's voltage, but the generator and the motor which moves the rudder are wound for 250 volts. The steering gear motor is compound-wound, taking series current from the armature of the motor driving the motor-generator, and the shunt field is strengthened by a relay at a definite overload on the motor.

There are four steering stands; three of them forward and one aft, anyone of which may be connected to the panel by means of a selective switch.

The controlling panel contains the necessary contactors for starting up the motor of the motor-generator set, as well as an ammeter and an overload relay, for the generator the necessary field switches and ammeter and voltmeter, also the motor field relay for strengthening the field of the steering gear motor and a step-back relay which inserts resistance into the field of the generator in case of excessive overload, performing the same purpose as the overload relay in the rheostatic system previously described.

The various steering stands have three speed positions in each direction; in the first, the field of the generator is excited to give a low voltage for slow speed; the next step strengthens the

field, and the next step fully excites the generator field, giving full speed of the motor.

The limit switch, which is operated by the steering gear, is provided to cut off power at an extreme movement in either direction without interfering with the return motion after the steering stand is reversed.

In connection with this system, the same criticism may be offered as regards size, weight and power required to operate the motor-generator, as was mentioned in case of the Pfatischer system.

Description of 150-h.p. System on Battleship *Texas*

It is not the purpose of this paper to draw close comparisons between the features and merits of the several electric systems of different manufacturers which have been proposed or installed and which are at present receiving the close attention of the Navy Department and others interested, but rather to point out the salient features of these different systems. Our future remarks apply largely to the system previously referred to, taking power directly from the dynamo mains, with which the writer is most familiar and from which also our data have been principally obtained. As an illustration of this system and of many of the points to be covered in the design of an electric steering gear we give a description of the apparatus and design of the installation on the battleships *Texas* and *New York*.

The electric installation on the *Texas* and *New York* (and with few minor differences those of the *Des Moines* and *Chester*, later transferred to the *Mississippi*, were exactly the same except as to reduction in horse power) includes the electric motor with disk brake installed in the steering motor compartment as illustrated in Fig. 4, the main automatic controller and resistance near the motor, and, in the compartment where the screw gear is located, a limit switch; master controllers or steering stands are furnished, one on the bridge, one in the conning tower, one in the central control station and one in the steering gear room. The steering stand is shown in Fig. 5, and contains within, a reversing switch for governing the main contactor controller in the motor room. The reversing switch is operated by the lever shown, and closes the circuit to the contactors of the automatic controller through several contact fingers. A latching device retains the lever in the center position; the pressure of the hand on top of the lever releases the latch, while a centering

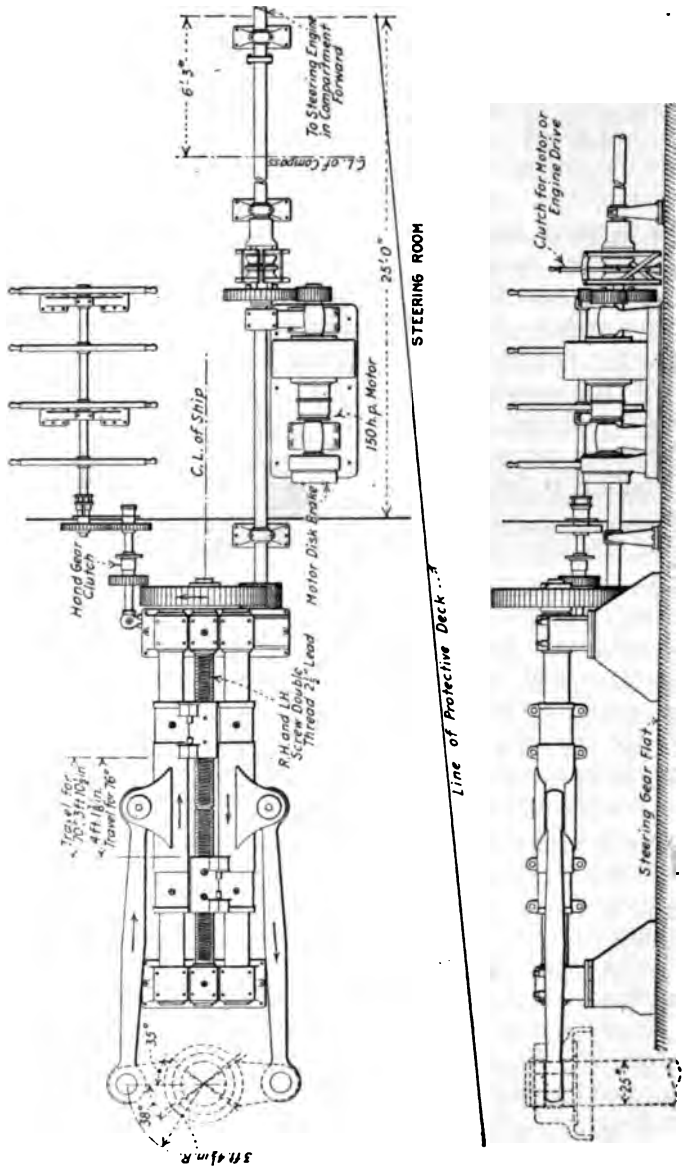
To Steering Engine in Compartment Forward
6'-5"
C.L. of Compass
25'-0"
STEERING ROOM
150 h.p. Motor
C.L. of Ship
Motor Disk Brake
Hand Gear Clutch
R.H. and L.H. Screw Double Thread 2½" Lead
Line of Protective Deck
Total for 30°: 3 ft 10½ in
4 ft 1 in. Travel for 70°
35°
38°
Clutch for Motor or Engine Drive
Steering Gear Flat
25°

FIG. 4

spring acts to return the lever to the "off" position, and should the hand be removed from the lever in a running position it will immediately restore itself to the central point, when the motor will be instantly stopped.

The stand is so arranged that a small movement of the lever causes the motor to start and run at a low speed, and further relatively large movements cause the motor to accelerate at once to full speed. Throwing the lever in the reverse direction reverses the rudder motor, so that it is simply necessary to throw the lever to right or left according to direction in which it is desired to move the vessel. About 60 deg. movement of the operating lever in either direction gives full control, including starting, stopping, slow and fast speeds and reverse, which feature commends itself to the helmsman especially, as quick work is frequently required in maneuvering the vessel. All the metal parts of the steering stand are brass and no magnetic interferences are occasioned by installing it near compasses.

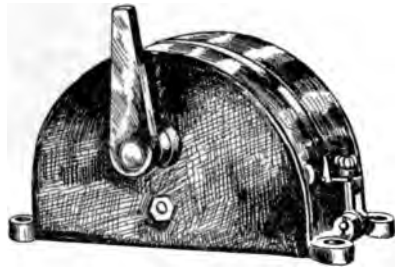

FIG. 7

As no follow-up control is involved, the rudder will keep on moving as long as the operating lever is held in the running position, and is stopped by the spring return of the lever to the central point, which in the possible case of casualty to the helmsman would prove advantageous. Should the rudder for any reason, however, fail to stop before the limits of travel are reached, a limit switch shown in Fig. 7 is provided to prevent the jamming of the gear at the hard-over positions. For this type of control the position of the rudder is at any instant determined by reference to the helm angle indicator always adjacent to the steering stand.

The main control panel shown in Fig. 6, with its front sheet metal covers removed for the purpose of illustration, provides contactors for the reversal of the armature, for cutting out resistance and accelerating the same, for operating at slow speed and for dynamic braking in the off position. An overload device is provided also, which in the event of jamming the gear or other extreme overloads automatically limits the current on the motor to a safe value, and by its use the necessity of circuit breakers

and fuses, whose blowing would be very dangerous to the operation of such a system, is obviated. The electrically-operated switches not only provide effective means for commutating the motor circuits but they permit the running of wires of a very small section to the steering stations, and as these small pilot wires can all be carried in one lead and conduit, this feature is of the utmost importance.

The switches are of a very strong construction and easily capable of standing the repeated operations of the steering gear. The resistance used in connection with the controller is of the cast grid type and also especially designed for heavy duty. In the lower right-hand corner of the cut is shown a small double-pole switch which functions as a selective switch for delegating the control to one of two steering stations. This switch was afterward changed in design, however, to provide for control from four or five different stations and so arranged as to make it impossible to steer from more than one station at a time.

The limit switch previously referred to, consists of a small, drum controller whose segments are connected in series with the secondary circuits from the main controller, so that when the dogs connected to the traveling nuts of the screw gear engage the lever of the limit switch at the hard-over position and open the same, the main contactor switches are opened and the equipment immediately shut down, assisted by dynamic braking and the motor disk brake on the armature shaft. The connections are then such that the rudder can be brought back in the reverse direction by movement of the steering stand lever in that direction, and when the rudder moves away from the extreme limit position the switch is restored to its normal position automatically by a centering spring.

The combined motor and disk brake used in this installation is shown in Fig. 8. The motor is rated at 150 h.p., 250 rev. per min. at 120 volts. The motor is especially designed with overload capacity to operate the rudder under severe conditions, taking care of the power required to operate under the infrequent conditions of rudder at extreme angles with vessel going ahead and backing at full speed. The windings of the motor, about 50 per cent series and 50 per cent shunt, give variable speed and torque characteristics and take advantage of the variation in load from center to hard-over positions, giving a quick response to the rudder, especially in the central angles, and heavy torques at the extreme angles, and permitting the installation of

an equipment smaller in rated horse power than would otherwise be required, especially as compared to a steam engine, which point has been previously brought out. The motor is capable of carrying 100 per cent overload for short periods of five minutes or more.

This installation was made as an auxiliary to the steam gear and the requirements for the operation of the rudder were 20 deg. right to 20 deg. left in 20 seconds, as against 35 deg. right to left in 20 seconds for the steam engine, and naturally resulting in a smaller equipment than if full duty had been required. In the case of a later battleship, the electric gear is required to operate the rudder at the same time as the steam engine and this system has, therefore, been provided, for that vessel, of 300 h.p. capacity, dividing the same between two motors of 150 h.p. each.

Calculation of Horse Power for the Above Installation

When a vessel is underway and the rudder is at some angle with reference to the keel line of the ship, the water impinging on the rudder surface undergoes a change in momentum, the result of which is dynamic pressure against the rudder and twisting moment about the rudder stock. The center of application of this pressure on the rudder, which varies with each angle, may be found by the use of some empirical formulas. An empirical formula is required, as the lines of action of the various streams of water are in different directions at various parts of the rudder, due to the shape of the vessel's stern, the influence of friction against the hull, the action of the propellers, etc. In navy work Joessel's formula is principally used, in which

d = distance of center of pressure from forward edge of rudder
b = breadth of rudder
a = angle made by plane of rudder with line of motion

$$\text{then } d = 0.195b + 0.305b \sin a$$

The twisting moment about the rudder stock is, of course, the product of the total resultant pressure on the rudder area, and the distance d of the point of application of the pressure from the center of the stock.

Let P = total pressure on the rudder in pounds
V = speed of ship in knots
A = area of rudder in square feet
b = horizontal length of rudder plane
d = distance of center of pressure from leading end of rudder

a = angle of rudder with fore and aft plane

$$\text{then } P = 4.6\, K\, A\, V^2 \times \frac{\sin a}{0.39 + 0.61 \sin a}$$

Usually 35 deg. is the maximum helm angle, in which case

$$P = 3.57\, K\, A\, V^2 \qquad\qquad d = 0.37\, b$$

For battleships and cruisers K varies from..... 0.60 to 0.75
" gunboats and small slow vessels of 900 tons and up, K varies from.....0.55 to 0.65
" torpedo boats and destroyers K varies from.. 0.45 to 0.55

A small coefficient is associated with small vessels, relatively large rudder areas, high speed of the ship and low speed of helm; and a large coefficient is associated with large vessels, relatively small rudder areas, low speed of ship and high speed of helm.

Theoretically the pressure P will increase to an angle of 45 deg. but ordinarily 35 to 40 deg. is the maximum angle of rudder throw. The equipment must be of sufficient size so that when the rudder is near the hard-over position sufficient power is available for its operation, and this point is, therefore, of chief importance in design and rating of the motor. In the case of the steam engine it is considered that with one-half of the full boiler pressure on one cylinder it should have sufficient torque to move the rudder, the crank of the other cylinder being supposedly temporarily on the dead center.

The pressure P and the center distances d are determined from the above formulas for a number of rudder angles, ranging from center to hard-over position, and the twisting moment in foot-pounds torque for each angle obtained as the product of the two.

After obtaining the twisting moment on the rudder the turning moment at the prime mover is to be ascertained by taking into account the gearing and friction losses and the angularity of the connecting links in the case of a screw gear.

The calculated, or actual curves if available, of the compound motor which it is desired to use, are then set down, as illustrated in Fig. 9, in the form of percentage speed and load curves, it here being of the greatest importance to select the characteristics of the motor in such a way as to take the greatest advantage of increasing torque with increase in rudder load.

A curve sheet is then prepared of rudder torque, horse power and speed, as shown in Fig. 10. The rudder torques are figured for the various angles from the formulas, and the percentage rudder torque curve then calculated, allowance being made, however, in the rudder torques for friction of the rudder stock, which in this case has been assumed to be 25 per cent of the normal calculated rudder torque. On curve sheet Fig. 9 it will be noted that the motor characteristics have been chosen to give 280 per cent torque at 100 per cent overload on the motor, and as we desire the motor to have about 100 per cent overload

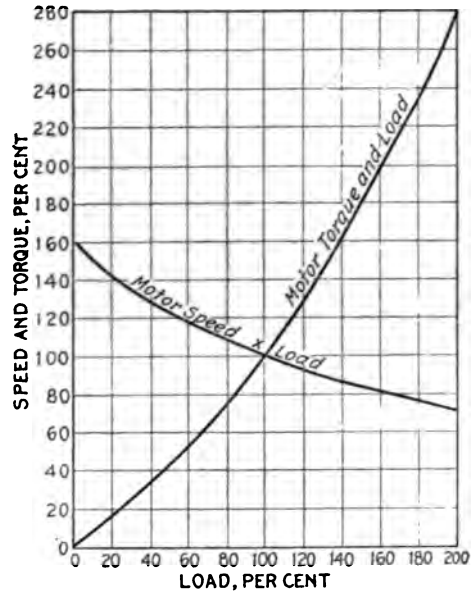

FIG. 9—CALCULATED CURVES FOR ELECTRIC STEERING GEAR FOR U. S. S. *Texas*

at 35 deg., the total rudder torque at 35 deg. therefore represents 280 per cent torque. The torque at 35 deg. representing 280 per cent, the 100 per cent point of the percentage curve is readily found, as is also the corresponding normal point of calculated rudder torque from which it is obtained by adding the 25 per cent for friction. We have thus obtained the percentage torque curve and the 100 per cent point, where the motor, of the characteristics which we have chosen, reaches 100 per cent torque full load and normal speed and which point, it will be noted, comes at 16 deg. of rudder travel.

From the motor curves in Fig. 9 the percentage motor speed curve can now be easily figured in per cent of motor speeds for the rudder torque or load at the various angles. Having obtained the percentage-torque and percentage-speed curves, the percentage-motor-horse power curve is readily obtained as the product of the two. As it is then necessary to figure in this case the motor speed over the required range of 20 deg. each side of the center, a number of points are taken on the percentage motor speed

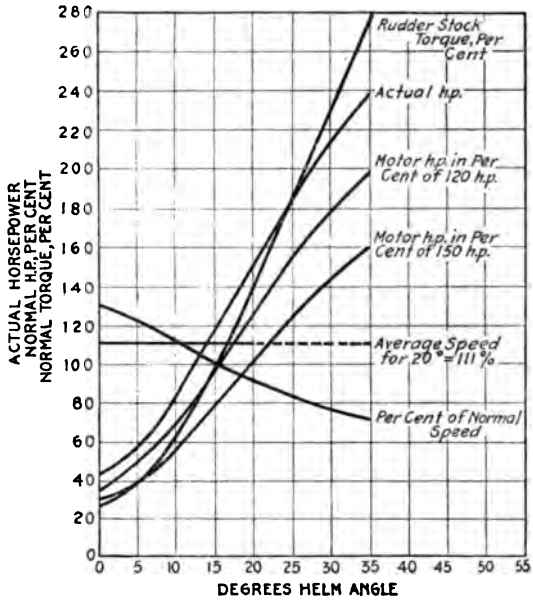

FIG. 10—U. S. S. *Texas*, CALCULATED RUDDER TORQUE AND POWER CURVES

Maximum rudder torque and power calculated from 1,860,000 ft-lb. at 35 deg. rudder angle.
Friction of rudder stock 25 per cent of normal rudder torque.
Efficiency of gearing 35 per cent.
Compound motor rated 150 h.p. used. (Curves based on 120-h.p. motor).

curves from 0 to 20 deg. and the average obtained, giving us in this case an average motor speed of 111 per cent over a range of 20 deg. of the rudder travel.

The requirement that the rudder must be operated 20 deg. right to 20 deg. left in 20 seconds gives a rudder speed of 0.333 rev. per min., which is the constant average speed of the rudder throughout this range. Dividing this quantity by 111 per cent, a rudder speed of 0.3 rev. per min. at full speed of motor is ob-

tained and which, it will be noted, obtains at the 16 deg. angle. With this figure as a basis the rudder speed for the other angles of throw are obtained from the per cent speed curve. From the figures of rudder speed and the corresponding torque in foot-pounds at this same angle, the horse power at the rudder stock for each angle is obtained.

From the curve sheet it will be noted that the rudder torque at 35 deg. is 1,860,000 ft-lb., and at 16 deg., 664,300 ft-lb. Therefore, the horse power at the rudder stock at 16 deg. of the rudder is 38, as obtained from the following formula.:

$$\text{h.p.} = \frac{\text{torque} \times 2\pi \times \text{rev. per min.}}{33{,}000} = \frac{664{,}300 \times 2\pi \times 0.3}{33{,}000} = 38$$

It will be further noted that the assumption has been made in the curve sheet of 35 per cent efficiency for the screw gearing, which then gives us a normal horse power of 108.5.

From the arrangement of gearing shown in Fig. 4 it will be noted that the screw has a lead of 2½ in. and a radius of yoke 40½ in., therefore, the revolutions of the screw in 10 sec. equal

$$\frac{\sin 20 \text{ deg.} \times 40\tfrac{1}{2} \text{ in.}}{2\tfrac{1}{2}} = 5.54 \text{ rev.}$$

For one minute the revolutions of the screw would be 6 × 5.54, or 33.24 rev. per min. With an average motor speed of 250 × 111 per cent, equal to 277 rev. per min., we have a ratio between screw shaft and motor speed of 33.24 to 277, which, therefore, gives us an indication of the spur gear ratios which are to be installed between the screw and the motor.

The ratio then determined should now be checked against the torque required to move the rudder at 35 deg., considering the effect of the angularity of the screw gear links, to see if the motor has sufficient torque available for the work under these conditions.

$$\text{The torque ratio at 35 deg.} = \frac{40.5 \times \cos 35 \times 2\pi}{2.5} = 83.5$$

$$\text{Therefore, } 83.5 \times \frac{277}{33.24} = 694 \text{ to 1, total ratio at 35 deg.}$$

$$\text{Torque required at 35 deg.} = \frac{1{,}860{,}000}{694} = 2680 \text{ ft-lb}$$

Motor torque required at 35 per cent efficiency of gearing

$$\frac{2680}{0.35} = 7675 \text{ ft-lb.}$$

It will be noted the curves were originally based on a 120-h.p. motor, the normal load coming at 16 deg. and 100 per cent overload at 35 per cent, and the calculations above would seem to indicate that this motor would have been sufficient for the service. The government did not wish to see a motor of less than 150 h.p. installed, and this was provided. Later tests on other installations indicated also that more power was required in backing than going ahead and that the 35 per cent efficiency would probably not be obtained, and, therefore, the gear ratio as actually installed was for an average motor speed of about 317 instead of 277 rev. per min. Our gear ratio is therefore 33.24 to 317 and the torque ratio at 35 deg. would be $83.5 \times \frac{317}{33.24} = 796$ to 1, instead of 694 to 1. Therefore, torque required at 35 deg. $= \frac{1,860,000}{796} = 2335$ ft-lb. Motor torque required at 35 deg. $= \frac{2335}{0.35} = 6675$ ft-lb.

The curves of actual torque, horse power and speed of the 150-h.p. motor used on the equipment are shown in Fig. 11, and it will be noted that the above calculated torque of 6675 ft-lb. is equivalent to about 80 per cent overload on the motors, coming at a higher point than indicated on the horse power curve in Fig. 10, owing largely to the fact that the motor has slightly different characteristics from those assumed in Fig. 9.

Some Results Obtained

The results obtained from trial tests and service operation of the installations of this gear have been very satisfactory, and the official trials of some of these will be reviewed briefly.

As soon as the *Chester* installation was completed the early part of 1912 and the vessel put to sea, she was ordered to meet the *Carpathia* at the time of the *Titanic* disaster, and was engaged in this mission about a week during the initial trial of the gear, upon which she had to rely entirely for power steering and the only means of steering from the bridge. Shortly after the

completion of this duty she was ordered to the ice fields to report the presence of icebergs and was engaged in this work for several weeks. She was then in continuous service until placed in reserve about September of that year, and although the performance of her electric gear had been most satisfactory, the gear was then removed and installed on the battleship *Mississippi* and the *Chester's* steam gear replaced, owing to the fact that this vessel

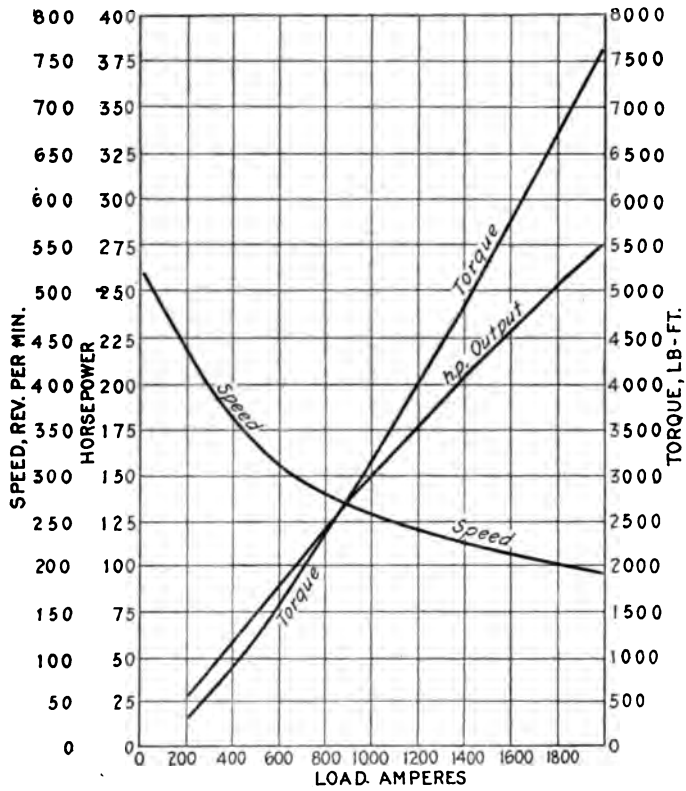

FIG. 11—ACTUAL CURVES—150-H.P. 120-VOLT, 250-REV. PER MIN., COMPOUND-WOUND, STEERING-GEAR MOTOR, U. S. S. *Texas*.

was supplied with a limited dynamo capacity. As the Department decided it inadvisable to increase her dynamo capacity, this procedure was necessary.

As a result of these trials and experiments on the *Chester* the commanding officer of that vessel reported that he considered this steering gear device unusually satisfactory, and an improvement on the steam gear with telemotor control:

1. In accuracy of steering
2. In the ease of operation for the helmsman
3. In the vibration of the ship
4. In the heat and moisture of the after part of the ship.

He further stated that he was surprised to see how accurately and with what little motion of the ship it was possible to steer, and that the response of the rudder to the movement of the master switch was rapid, and that the helmsmen were able to keep the ship on her course with small angles of helm and very little effort. The executive officer of the same vessel in his comments stated that " From my observation of this steering gear I should say that the non-follow-up master-switch type of control is entirely practical and suitable, and the quartermasters and helmsmen all prefer the master-switch control to the old wheel control."

It is, of course, very natural for an old seaman to throw his wheel to port upon receiving an order to starboard his helm, but the above comments show that these seamen are able readily to learn the new method, and one of its most natural advantages is that to steer the ship to starboard or port, or right and left, as it is now termed by the Navy Department, the helmsman has simply to throw the operating lever in the direction desired, which is the most logical operation to perform and in contradistinction to the old system, which was the reverse of a natural tendency.

An analysis of the conditions and of the electrical apparatus provided, indicates quite clearly that the above results would naturally follow, especially as compared with the steam gear equipment. The operation of the master switch is naturally easy for the helmsman, and there being no lost motion or mechanical parts between the bridge and steering room, the appreciable time lag with the old steam gear is eliminated. This absence of lost motion and the natural rapidity with which a motor, particularly of this design, can be accelerated, gives practically instantaneous response to the motion of the operating lever. Over the center angles of travel also, where the major part of the steering is done and load is light, the response would naturally be very prompt and the speed higher than at the extreme angles.

It was further noted by the officers of both the *Des Moines* and *Chester* that there was an appreciable saving in steam consumption over the steam engine, and it should be noted in this connection that with the steam engine some steam is always passing through the engine valves even with the rudder standing

still, causing a waste of steam in addition to that consumed in the operation of the engine, which is naturally of low efficiency. In the case of the electric gear, in addition to its natural high efficiency, the motor is started and stopped each time the rudder is started and stopped and the current is entirely cut off when the rudder is at rest.

A small amount of heat is generated in the rheostat control of the motor but it is quite insignificant as compared with that of the steam engine and not sufficient to cause any inconvenience in the compartments adjacent. On the *Des Moines* the officers' mess room is located not more than 20 ft. (6 m.) from the steering engine room, yet they reported no inconvenience whatever from the heat experienced, even in the tropics.

One of the officers on the *Des Moines*, after a cruise through the tropics, reported that with the temperature at 82 deg. fahr. on the bridge, that of the steering and engine room was 98 deg. fahr., and the comment was further made, which forms a very convincing argument in this connection, that a quartermaster on the vessel had complained that " in the old days when we had steam on here we could dry clothes in the steering engine room in twenty minutes, but now that place is no good for drying clothes."

We are also pleased to include the final comments of this officer, Ensign W. A. Edwards, in the article prepared by him for the Naval Institute Proceedings after he had served some time on both the *Des Moines* and *Chester*.

"From the intimate relations which I have had with this method of steering, from the most excellent results which I have seen produced and from the numerous advantages which it seems to possess over any other method in use today, I cannot help but feel that the electric steering gear is up-to-date and furthermore, that it has come to stay."

He further says: " In summation of the above remarks I would say that at the time of the present writing, Nov. 15, 1912, the *Des Moines* has covered 3600 miles (5793 km.) in continuous service, most of which was done in the tropics, during which time the electric steering gear was used constantly without a single breakdown of any kind."

With reference to Ensign Edwards's above statement, the writer wishes to explain, however, that thereafter a few minor difficulties were experienced with the *Des Moines* gear due to breakage of certain parts, owing to the largely experimental nature of her equipment. The installation was recently overhauled at the

navy yard, the minor defects in this first installation remedied, and the *Des Moines* is again in the tropics with the electric gear as the only means of steering.

The battleship *Texas*, the special description of whose gear is given above, was during the latter part of October on her official trial trip, lasting in all about 12 days. As she left the shipyard the steam steering gear was in use and the electric gear not thrown in until about a day later when the vessel was some distance up the coast. Although this electric gear was an entirely new equipment to all those on board and in charge of its operation, it at once made friends and the steam gear from that time until the vessel returned to the shipyard, about ten days later, was not put into operation except for two or three hours to actually try out its operation, and the electric gear was immediately thrown in again after this short steam trial. The power required in the operation of the electric gear, both in tests going full speed ahead and full speed astern, is shown on the curve sheet in Fig. 12. In going astern the engine revolutions were about 80 per cent of the revolutions at full speed ahead.

The curves taken from the recording ammeter used during the trials, while giving a good relative indication of the performance of the gear at various points in the rudder travel and under various conditions, cannot be taken as an accurate representation of actual motor values, the meter in question having met with an accident during the preliminary trials which required repairs at sea without an opportunity of careful re-calibration, and as compared to portable direct-reading test meters which were also used and the dynamo room meters the recording meter, shows at times an excess of current values of 25 to 35 per cent. In the case of the peak starting currents, however, the inertia of the switchboard and test meter needles would probably prevent them from reaching as high values as the recording meter, which is more sensitive.

Reference to the curve sheet from the recording meter indicates the most severe conditions were imposed at full speed astern. On some of the backing tests the interruptions to the steady flow of the current were caused by the helmsman, when he saw no immediate indication of rudder travel on the helm angle indicator and believed that at the moment the motor was not moving. As a matter of fact, the motor was turning very slowly at the points of interruption until finally about the 22½ deg. rudder position was reached, when the motor accelerated quite rapidly. After

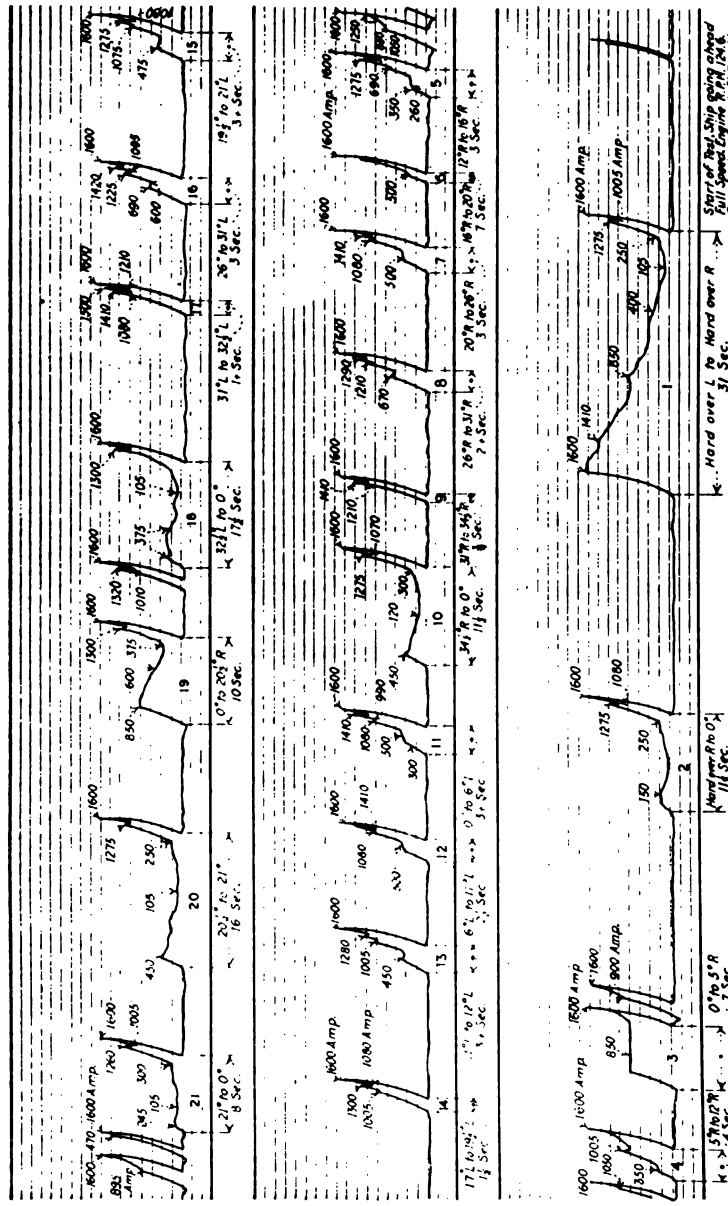

FIG. 12A.—GRAPHIC RECORD OF TEST, 150-H.P. STEERING GEAR MOTOR, U. S. *Texas*

Tests made while off Cape Charles, Va.—Line volts, 120.

this the load fell off gradually as the rudder became more nearly parallel with the stream lines. When past the central position the water pressure against the rudder, due to the backward motion of the ship, actually assisted the motor.

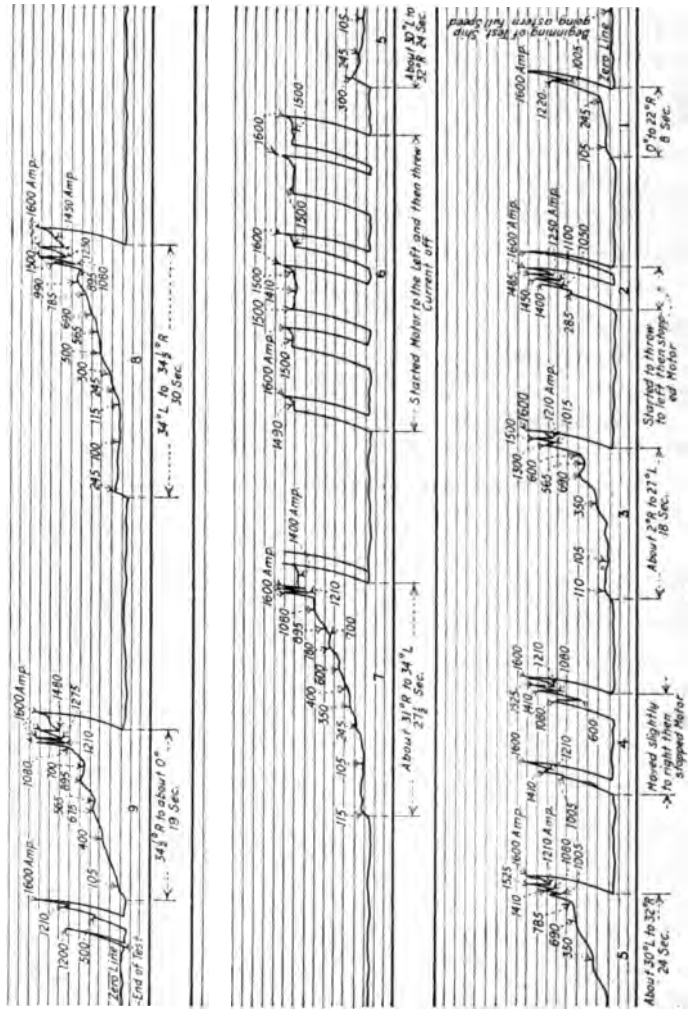

FIG. 12B—GRAPHIC RECORD OF TEST, 150-H. P. STEERING GEAR MOTOR, U. S. S. *Texas*
Tests made while off Cape Charles, Va.—Line volts, 120.

The rudder was turned from 20 deg. right to 20 deg. left, going full speed ahead, in about 16½ seconds, and from hard-over to hard-over in about 31 sec. The starting current on the direct-reading meters was about 1250 amperes. (The recording am-

meter at the same points indicated about 1700 amperes.) This refers to the full speed position with master controller thrown promptly to the last point. About 800 amperes were required on the first or slow-speed notch, which was also similarly indicated by the recording meter. On this slow-speed position the motor made about 150 rev. per min.; on the second or full-speed notch the running current frequently varied from 150 to 400 amperes, depending upon the position of the rudder, with a motor speed of 300 to 400 rev. per min., except at extreme angles, where the current increased rapidly and the motor speed decreased as shown by the curves.

The following data were taken during the official trial trip with the direct-reading meters:

	Ampere Peak	Ampere Steady	Volts
Ship at anchor			
full speed position	1220	150	120
half " "	1220	800	"
Ship full speed ahead,			
full speed position	1220	110 with stream	"
		400 against "	"
half speed position	1220	800	"
Ship full speed astern			
half speed position	1300	800 all conditions	"
full " "	1300	150 near amidship	"

Running astern full speed, with motor on full-speed control point, steady amperes started about 1100, turning rudder from hard-over position towards center, and dropped to 150 amperes near center line of ship. In starting from hard-over position the rudder movement was very slow, increasing as the rudder neared the center line.

The following data were taken on dock trial on the gear before leaving the shipyard.

Line volts 120; amperes max. 1200; steady 116; rev. per min. 410 (second notch).

Time for rudder travel 20 deg. right to 20 deg. left, 15 sec.

Time for rudder travel " hard-over to hard-over " 70 deg. total, 26 sec.

In connection with the *Texas* trials it may be stated in general that great satisfaction was expressed by all those on board at the results obtained. And if we assume that 1600 amperes as indicated by the recording meter was the maximum running current required (which is certainly high owing to the errors of the meter explained above), it will be noted, from the curves in Fig. 11, that this corresponds to 60 per cent overload on this *150*-h.p. motor or 100 per cent overload on a 120-h.p. motor. It

therefore appears that there was considerable reserve power available for turning under the extreme conditions, and that the original motor calculations based on 120 h.p. as shown on curve sheet Fig. 10 would have been quite sufficient for the requirements. In connection with the time of 16½ sec. actually obtained to operate the rudder through the 40 deg., it may be stated that in the calculations the total time was taken as twice that required to travel from 0 to 20 deg. and no allowance made for the increased speed of the rudder in traveling with the stream lines from 20 deg. to 0. This accounts largely for the difference between the 16½ sec. obtained and the 20 sec. required.

From the above data and results obtained on tests of other installations it has been found that the power required to turn the rudder changes greatly with the varying conditions which will obtain during the steering of the vessel, and the deduction would appear to be warranted that the maximum torque required when moving the rudder from zero to hard over is greater than that required when moving from about 20 deg. to hard over after running for a brief period at the 20 deg. position. Also that the maximum torque required when moving the rudder from hard over to hard over is greater than that required for moving the rudder from zero to hard over. This, it is believed, can readily be accounted for by the change in direction of the flow of water against the rudder. If the rudder is at 20 deg. and the vessel turning, the direction of the stream lines is not nearly so perpendicular to the plane of the rudder as would be the case if the rudder were at zero and moved to hard-over, the hard-over position of the rudder being attained, of course, before the vessel had answered its helm. Similarly, if the rudder is at the hard-over position and moved immediately to the hard-over position in the reverse direction, the direction of flow of the water against the rudder is more nearly perpendicular to its plane than would be the case under either of the conditions mentioned.

From the above it is apparent that no definite deductions can be made as to the efficiency of the mechanism without taking into account the exact conditions under which readings are taken, especially with reference to the angle of stream lines against the rudder, as data taken under various conditions would seem to indicate an efficiency of the mechanism ranging from about 23 to 35 per cent. In the case of the *Texas* our assumption of 35 per cent total efficiency for the gearings was apparently very nearly correct.

The results obtained from various installations show interest-

ing facts regarding power required to move the rudder when backing. In the case of the *Mississippi* the backing test showed much more power to be required in backing than in going ahead. In the case of the *Texas*, however, the backing power is but little different from that required at full speed ahead, which we assume may be accounted for by a difference in balancing of the rudders for the two vessels, as a difference in the amount of rudder balance would naturally produce a difference in this respect. It is ordinarily assumed that the condition imposed in backing is much more severe than going ahead and the results obtained with the *Texas* on this point, are, therefore, especially interesting.

Conclusions

In conclusion, we believe that the results from trials and service operation of these several installations show that the results previously enumerated to be accomplished by the use of the electric drive have been fully attained. The popularity of the electric gear with those who have been concerned in its operation would seem to have been clearly established, and in addition to a saving in weight, space and efficiency, an ease and accuracy of control has been obtained which has not only eliminated all effort for the helmsman in steering the vessel but has enabled him to keep on the course with smaller and fewer movements of the helm.

The results on the *Texas* have shown that our calculations of the horse power required were fairly accurate and the results obtained have indicated that the capacity actually installed was more than necessary, and considering the fact that the rudder on this vessel was operated through the required 40 deg. in 16½ sec. instead of 20, which would have permitted a still greater ratio of gearing to have been installed within the requirements, it is apparent that had such a gearing been provided, a motor but little in excess of 100 h.p. rating of this type would have been sufficient for the work. This is in marked contrast to the size and rating of a steam engine which would be necessary for the same service. It may be noted also in this connection what a large proportion of the power is used in the operation of the screw gear itself, and where a more efficient type of gear is employed the motor horse power would be still further reduced.

In view of the above it appears to us that the electric gear is up-to-date and has come to stay and it does not seem, therefore, too much to predict that electricity will in the future be used generally as the power for the steering of vessels.

DISCUSSION ON "ELECTRICITY THE FUTURE POWER FOR STEERING VESSELS," (HIBBARD), NEW YORK, MAY 19, 1914.

G. A. Pierce, Jr.: We do not agree with the author that the American navy has been the most conspicuous exception to the limited use of electricity in marine work. In 1902 on the Russian battleship *Retvizan*, building at the time the U. S. S. *Maine* was building, the generating plant was 528 kw. compared to 328 kw. on the *Maine*. Remote control contactors were used exclusively in connection with turret turning, ammunition hoists, elevating and rammers, which at that time had not been contemplated in the American navy and only used to a limited extent in this country. Six-inch bilge pumps were operated by 60-kw. motors, six in number; electric steering gear; electrically driven forced draft fans; six-pounder and three-inch ammunition hoist operated by remote control—none of which was in use or contemplated at that time in the American navy. Furthermore, the step-by-step motion for interior communication apparatus, recently adopted by our navy, was used. The majority of the systems were copied from the French navy at that time. Prior to the adoption of electric heating in the U. S. navy ships, several merchant vessels were thus heated, not only in America but in England, and the extended use and development has been retarded owing to the lack of engineering in connection with these early installations. Electric steering gears, windlass and capstans and in fact, every use in which electricity is at present employed, has been previously used both in the merchant marine and in other navies.

While our recent achievements are very creditable, we should not look on them with too much pride.

Referring to the question of control of steam steering gears, I thoroughly agree with the author, particularly when I recall one installation in a cruiser with shafting from the pilot house to the steering engine room. When the vessel was loaded and maximum temperatures were reached after all fires in the boilers had been lighted it was impossible to move the shafting, and resort was made to the electric telemotor which previously had been installed as an auxiliary, and this electric telemotor was used to operate the vessel thereafter, although the system of shafting was made to operate with some degree of success. In most steam gears where hydraulic telemotors are used, it is customary to supply an indicator to tell when the transmitter and the receiver of the hydraulic system are in synchronism. This is required because of leaks in the system, and clearance in the pistons.

Referring to the results to be accomplished by electric steering, we do not agree with the author that the noise has been greatly reduced, especially with the system using contactors, as their constant operation is attended with noise. Furthermore, the electric control is not, in my opinion, the simplest means of control, as we can conceive of nothing simpler than the wire rope

transmitter with Hanscom drum for operating a steering gear and any troubles are more easily traced and found than is possibl with an electric gear, with all the electric wiring and circuits an its multiplicity of contacts.

Referring to the history of electric gears, we desire to take ex ception to the author's statement that in recent years, only, ha the matter been given sufficient attention and the electric appara tus developed to such a point as to permit of successful result being obtained, and we point to the succeeding page of the pape for illustrations of early and successful steering gears, namely Russian ships, and the *Finland*, *Minnesota*, and *Dakota*, and w believe these were not only some of the first, but the firs successful electric steering gears used.

The remainder of the paper is devoted to the description o rheostatic control gears, and we note the author's remark " it i not the purpose of the paper to draw close comparisons betwee the features and merits of the various systems." We think however, in view of some other statements in the paper, som further remarks relative to other systems are essential.

If we approach the question of electric steering gears from a engineering standpoint on the basis of the requirements lai down, we require the following:

A gear for frequent starting and stopping and for short move ments to right and left of central line, for maximum torqu regardless of speed, as the speed depends on the design of th gear used, easy starting and stopping to prevent wear, one with minimum number of parts and contacts to become deranged. I a maximum of the above can be obtained in one gear th question of per cent efficiencies drops into insignificance, so lon as the gear is not positively wasteful.

The speaker is of the opinion that the Pfatischer gear come nearer the solution of this problem from an engineering stand point than the rheostatic control, although, commercially, th rheostatic control may have some advantage.

The rheostatic control as applied to steering gears appears no to be the engineering solution of the problem. The line curren with full line voltage for every movement is used with the resist ance to control the amount of energy for the work to be done, an this seldom amounts to the rating of the motor when compare to the number of operations, and in that event a brake is applie to stop the momentum imparted. It should be noted that 2 seconds is usually the longest time run, and during this perio to start the motor, eight or ten contactors are used to bring th motor to full speed, dynamic braking as well as disk braking t stop the operation and a limit switch installed to prevent over travel.

The pumping of so large a motor is sure to affect seriously th voltage of the entire system, as we note from the curves, 10 peak of 1600 amperes or 200 kw. in approximately two minutes.

Relative to the follow-up gear, it does not appear in the pape

and we have never been able to obtain satisfactory explanation, what advantage is to be obtained by its elimination. It is an automatic stop for the system, as well as an indicator of the position of the rudder at all times, and when not installed its functions are supplemented by a rudder indicator which is very seldom installed on merchant vessels, and also by the automatic spring in the reversing switch on the bridge, as described in the paper, to operate in the event of accident to the helmsman. It is our opinion that the advocates of the non-follow-up system are misguided.

In conclusion, the electric steering gears as designed, installed and operated successfully for twelve years, have perhaps one-tenth the pieces of apparatus and one-thirtieth the number of connections of the gear advocated in the present paper, and as the author of the paper was intimately connected with the selection of the steering gear for the *New York* and *Texas* it would be interesting to know if the decision was reached on an engineering or a commercial basis.

Mathias Pfatischer: In regard to the criticism that a small Pfatischer gear as installed on the cruiser *Montgomery* requires a current consumption of 25 amperes at all times the rudder is not being operated, I looked up my records and found that the amount is about one-half of that stated.

As regards the difficulty mentioned of getting a sufficient operating voltage by the use of the Wheatstone bridge connection, I have never found such to be the case. As a matter of fact I could get about 40 volts on the third contact from zero, and nearly full voltage on the sixth point. I have found that for successful electric ordinary steering of a steamer not more than about 40 volts are required; it varies from about 10 to 40 volts across the steering gear motor armature terminals. Full voltage is required only on rare occasions. This indicates to me that a constant voltage system will hardly constitute a proper solution. I have found in my work in the past that the amount of power required for steering a straight course across the Atlantic is very small. On the Red Star liner *Finland*, which is of 10,000 tons and has a speed of 16 knots, the current consumption never exceeded 15 h.p.

I cannot agree with the author of the paper that the steering gear which he has described marks an advance in the art and believe it has never been tried out under adverse conditions, such as, for instance, in steering a ship through a crooked channel. It seems to me it is considerable of a disadvantage for the quartermaster to have continually to watch the rudder indicator, because it distracts his attention. He should be looking at the compass and the bow of the ship instead of the indicator. He should know that when he moves the steering wheel or pointer to say five degrees right or left that the rudder would move to that point and stop automatically, without his having to pay any attention to the rudder indicator so he may know when to cut off

the electric power. The gear described is not fool-proof, which a successful electric steering gear, in my opinion, must be.

Maxwell W. Day: In referring to the systems using motor-generator sets, criticism has been made concerning the weight, size and cost, but there are certain advantages which should not be overlooked.

1. It has been shown that the starting peaks on the *Texas* gear amounted to 1600 amperes with a 150-h.p. motor. With a 350-h.p. motor these peaks would naturally be taken up to over 3700 amperes for a 120-volt ship, and further, the more rapid movement of the rudder from hard over to hard over will increase the working load more than in this same proportion. Mr. Hibbard has called attention to the fact that when the ship is turning from one extreme position to the other, the rudder requires greater power than when the rudder is moved from midship position to the outboard position.

In some tests made in the German navy a few years ago, it was found in going from hard over to hard over that the maximum pressure was obtained at about 30 degrees rudder position, instead of 38; the pressure being 71 tons at 30 degrees, while the pressure calculated from Middendorf's formula for 38 degrees shows 35.5 tons. On this account, a steering gear to operate at the high speed required on the recent ships, will require more than twice as much power as if the rudder were to move at one-half the speed.

On this account, the rheostatic system for some of the later ships would require contactors capable of operating with 4000 to 4500 amperes, and this, in itself, is a serious problem. If the use of these large contactors is to be avoided by the use of two motors, each of one-half capacity, a much larger number of contactors of smaller size is required, and the system of connections and interlocks becomes very complicated, especially if a series-parallel or parallel-series arrangement is to be used.

With a motor-generator, the contactors required for starting up the motor-generator set are very few in number and seldom used; so that the conditions for the few contactors required are very much more favorable.

2. With the rheostatic system a heavy peak of current is occasioned at the instant of starting and a large amount of energy is dissipated in the starting rheostat every time the motor is started. With the shunt motor the energy lost in the rheostat is practically equivalent to the kinetic energy of the armature at the speed required at the time the rheostat is completely cut out of the circuit, and with a compound motor somewhat less.

This is not mentioned on account of the question of efficiency, as the running-light losses of the motor-generator set probably just about offset it, but this system of starting requires a heavy load to be put upon the generating plant, practically instantaneously, and as the rudder in many cases is moved four times a minute, this produces a sudden fluctuating load upon the generat-

ing plant, which is objectionable from an operating standpoint, and criticism of this has been made in some cases. On the other hand, the motor-generator system avoids these peaks, because the motor is started up without the insertion of resistance, and the load is gradually applied to the motor by the building up of the field of the generator, and during the time that the rudder motor is operating at low speed, and requiring a correspondingly low voltage from the generator, the power taken from the generating plant is relatively small.

In addition to this, the compound winding of the motor-generator set slows down the speed as the load is applied, thus transforming a portion of the kinetic energy for the accelerating of the rudder motor armature.

3. As the rudder torque increases very rapidly as it is moving away from the midship position, it is desirable to increase the torque per ampere of the motor, which is done in the rheostatic system either by using a compound-wound motor or by automatic strengthening of the field of a shunt motor, but in addition to this feature, the generator of the motor-generator system is provided with a drooping characteristic by means of a reversed series winding, so that the amount of power required is very much reduced, and this same effect is increased by the compound winding of the motor of the set, which reduces its voltage still further by reducing the speed of the generator. In this way, the power taken from the generating plant is increased at light loads and reduced at heavy loads, to a greater extent than is available with a compound motor, working on a constant potential system with rheostatic control.

4. Further, with the rheostatic system, the stopping of the rudder motor armature is accomplished by a dynamic brake and a mechanical brake, so that the kinetic energy of the armature is transformed into heat; but in the case of the motor-generator system, a considerable portion of this energy is stored up again in the increased speed of the motor-generator, and will be available for use at the next time that the rudder motor is started.

What has been said concerning the motor-generator system, applies, to a considerable degree, to a separate generator operated by its own prime mover, except that with a regulating governor used on generating sets, the speed of the generator will be practically constant, and therefore, does not have the same advantage in storing up kinetic energy at increased speed.

5. Reference has been made to the Pfatischer system. This system is provided with a follow-up control. It has the advantages mentioned above as applying to motor-generator sets or separately driven generators, and has the further advantage that it allows the use of an extremely simple type of follow-up control.

Reference has been made to some of the Russian ships, and in this connection I will mention that the Russian cruiser *Pallada* and German cruiser *Aegir* were equipped with the Essberger gear. This consisted of two shunt motors running in opposite direc-

divided, so that any contactor does not carry more than about 1000 amperes as a maximum. The two motors are instrumental in cutting down the peak rushes of current, and minimize the amount of power required at the smaller angles, at cruising speeds, etc.

As regards the dynamic current required in stopping motors, I would say these motors are especially selected, and operate at low speed, that is, comparatively low, and it has been found that it is quite possible to stop the motors without the use of the disk brakes at all, if you wish to depend to that extent on the dynamic effect. It is not so necessary to stop the motors quickly when the non-follow-up system is used. When the follow-up system is used, you must stop them with the quicker acting dynamic brake, to prevent any possibility of following over.

As regards the two systems in general, there is no question but that the rheostatic system may have a few more small parts, while the motor-generator system certainly has a greater number of large parts, and the weight is much greater, and, of course, the first cost, which may be incidental, is greater. There are of the two systems now sufficient installations being effected so that in a short time we will have results of the total power consumed by the two systems, and it is my prediction that the rheostatic system will show a total consumption over a considerable period of time appreciably less than the motor-generator system.

H. A. Hornor (by letter): The advantages of the contactor type of steering gear control have been clearly set forth by the author of this excellent paper. The disadvantages may be briefly stated as follows:

Contactors may be prevented at times from properly functioning due to the rolling and pitching of the vessel.

They may also be affected by the vibration of the vessel, which at high speeds in this location is often very severe.

In general the mechanical as well as the electrical wear and tear on this type of apparatus occasions very careful supervision and upkeep.

The current demands on the generating plant are too great and too frequent. The latest requirements for the design of generators for naval service state that, for 300-kw. sets, the speed variation must not exceed 4 per cent when full load is thrown on or off; and 3 per cent when load is suddenly varied from full load to 20 per cent of full load, or vice versa, when operating condensing at normal steam pressure. The jump in voltage must not exceed 12 per cent, or 15 volts in the case of a 125-volt machine, when full load is suddenly thrown on or off, under all the varying conditions of steam and operation. The author of this paper gives ammeter records for a 150-h.p. motor, 60 per cent overloaded. Current peaks of 1600 amperes in short variable periods of time are indicated. This represents 3/4 load for one 300-kw. generator. In the case of a proposed 300-h.p. outfit this would mean full-

load current peaks of 2100 amperes, or nearly full load for one 300-kw. machine. If 100 per cent overload is demanded, the current peaks would double, requiring full-load current from two 300-kw. generators; or the full load capacity of the after dynamo room. There would remain for the general supply of current to the ship 1600 amperes, or the 1/3 overload capacity of the two generating sets. Under practical working conditions on shipboard the jump in voltage averages about 10 or 12 volts—an amount which will affect the lighting and perhaps other installations.

The disadvantages of the motor-generator control are mentioned in the paper and therefore the advantages will be stated:

No contactors in continual operation.

Reliability insured by staunchness of design.

Reduction of supervision and upkeep.

The omission of the electro-mechanical brake.

Reduction of current peaks, thereby cushioning the loads on the generating plant.

Presented at the 295th meeting of the American Institute of Electrical Engineers, New York, May 19, 1914, under the auspices of the Committee on Use of Electricity in Marine Work.

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THE FUTURE OF ELECTRIC HEATING AND COOKING IN MARINE SERVICE

BY H. J. MAUGER

ABSTRACT OF PAPER

Indications of the future point to electric motor-driven propulsion and abandonment of coal-burning boilers. Electric cooking and heating is in line with this development and the source of heat for cooking and heating will be confined to the boiler room. The future of electric cooking apparatus is assured by the progress already made in the U. S. Navy in adopting electric equipment. Detailed report is given of trial trip of U. S. S. *Texas*, which depends almost entirely upon electricity for cooking. Consumption of 1.25 kw-hr. per person per meal is indicated. Load factor was 50 per cent.

Electric ranges and bake ovens effect considerable saving in weight and space and release cooks from being "firemen" to devote their time and effort to good cooking. Electric cooking finds greatest advantages in high temperature cooking.

Electric heating on shipboard does away with the disadvantages of steam piping and gives individual and local regulation and provides, where desired, glowing heat without fire.

Other accessories are the electric flatiron, the soldering iron and therapeutic devices.

IF we may be permitted to look into the future five or ten years, we venture to make the forecast that first-class vessels will be driven by electric motors, direct-connected to the shafts of the propellers, the electricity being generated either by steam turbine-driven generators, energized by steam furnished from oil-burning boilers, or else by electric oil-generator sets.

In assuming the role of a prophet, we naturally enjoy the freedom of a wide latitude and place ourselves beyond the sphere of criticism, but we believe that the members of this Institute will agree with us, at least, that signs point in that direction.

On board ship, very important, if not paramount, are the considerations of saving in space and weight, as well as considerations of cleanliness and convenience and despatch; and nothing that we know of at the present time so completely and satisfactorily meets these requirements for their purpose as the electric range and bake oven, with their culinary accompaniments, on the one hand, and the electric air heater on the other, not to

speak of such miscellaneous applications as the flatiron, the soldering iron, etc. In other words, in our vision of the model ship of the future, we can see no other source of heat and power than electricity, outside of the boiler or engine room.

When we realize that a number of the U. S. battleships, not to speak of submarines and army transports, recently constructed or in process of construction, have adopted electric cooking and heating in full or in part after the most thorough investigations, extending over a period of years, electric heating and cooking in marine service becomes an established fact, and it remains only to see what the future may bring forth.

Among battleships which have been partly equipped with electric cooking and heating are the *Arkansas* and *Wyoming*. The battleships *Texas*, *New York*, *Nevada* and *Oklahoma*, which are now under construction, have the galleys and bakeshops completely equipped. Already thirteen submarines have been equipped entirely, and eight more are in process of construction.

The *Wyoming* has three electric ranges in the officers' galley and electric cooking is there used exclusively; in the crew's galley, there are four electric ranges and four coal ranges. The *Wyoming* was equipped with the latest design of ranges December 24th, 1912, and has had no appreciable trouble, except with the hot plates of the cooking surface, which has since been overcome.

Recently the army transport *Thomas* returned from Manila carrying about 1500 troops and crew. Two type D-47 bake ovens, capacity 108 one-pound loaves, proved sufficient to bake all the bread, pastry, etc., required, although three ovens were available. No trouble was experienced, and everyone interested was pleased with their operation.

Of special interest is the recent trial trip of the battleship *Texas*, made during last October, because for the first time a large number of men (715) at sea were entirely dependent upon electric cooking for their daily meals. During the run of two weeks, there were no breakdowns of any kind and the cooking was done in a perfectly satisfactory manner.

The results of this trial demonstrated that the equipment was more than sufficient to take care of the ship's full complement, which will comprise about 1070 men, including 70 officers. This ship's equipment consists of 15 electric ranges, type D-48, and 2 bake ovens, type D-50, and with the exception of some

supplementary steam kettles and coffee urns in the crew's galley, there is no other means of cooking or baking available on this ship. The success of the trial is all the more apparent in view of the fact that none of the cooks had any previous experience in using electric apparatus and that they so readily became acquainted with its operation and had no difficulties in performing the duty required. The attendants, without exception, were pleased with the performance of the electric ranges, as well as the bake ovens, being much impressed with their greater efficiency and cleanliness.

The trial trip of the *Texas* is also significant because for the first time has it been possible to obtain such complete and valuable data.

Five ranges are installed in the officers' galley, four of which were in daily use; and in the crew's galley there are ten ranges, six to eight of which were used daily during the trial, as well as two bake ovens in the bakery. The officers' galley served 162 men and the crew's galley 553 men; a total of 715 men. The ovens proved to be of sufficient capacity to supply a crew twice as large as that aboard, and they were perfectly suitable for all kinds of work demanded of them. The officers' galley was in use from 6 a.m. to 9:30 p.m. (except an hour and a half from 2:30 p.m. to 4 p.m.). A few hot plates were kept in service at all times, supplying hot coffee. The crew's galley generally was in use from 4:30 a.m. to 8:30 a.m.; 10 a.m. to 1:30 p.m.; and 4 p.m. to 8:30 p.m., depending somewhat on the daily menus.

Referring to Fig. 1, the top curve shows the daily cooking load, in kilowatt-hours, which averaged 1258.6, the highest daily load being 1695 and the lowest 806 kw-hr. The downward slope of the curve shows a radical increase in economy as the cooks became accustomed to the use of the electric ranges, and the economy would be still further increased by longer experience. This consumption proved to be an average of 1.7 kw-hr. per person per day for the total; but further reference to the accompanying curve shows that the average total consumption of the crew's galley (556 kw-hr.) was only slightly more than that of the officers' (519 kw-hr.). The average consumption per man per day of the crew's galley was one kw-hr. as compared with 3.2 kw-hr. of the officers. The average daily consumption of the bakery was 182 kw-hr. total, or 0.25 kw-hr. per man. Without doubt, the total consumption for cooking and baking should not average more than 1.25 kw-hr. per day per person, instead of 1.7 kw-hr.

In accounting for the difference of the energy consumption per man in the officers' galley as compared with the crew's galley, we have to consider that there is no steam cooking in the former and this would account for 25 or 30 per cent of the total consumption. It should be further noted that the officers' galley was operated somewhat on the plan of an *a la carte* or

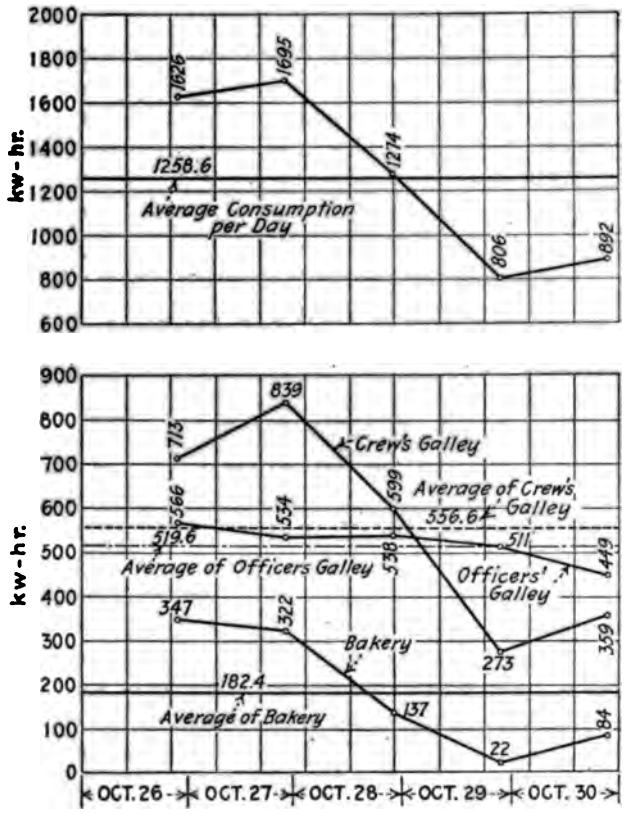

FIG. 1—TRIAL TRIP OF U. S. S. *Texas*

Total current consumption of electric ranges in bake ovens Oct. 26 to Oct. 30, 1913, inclusive. Officers' galley served 162 men; crew's galley 553 men; bakery served 715 men.

European plan restaurant where the meals were strung out over longer periods—more severe service than will actually be required when in commission; while in the crew's galley, advantage accrued from cooking for a much larger number of men at one time. Reference to the menus shown in the curves will indicate that the crew fared very well.

Fig. 2 shows the load curve for the ranges in the officers' galley on Oct. 30th, in which the total consumption was 451.7 kw-hr. The average kilowatt demand was 27.4 while the maximum (during the dinner period) reached 54 kw-hr. Four

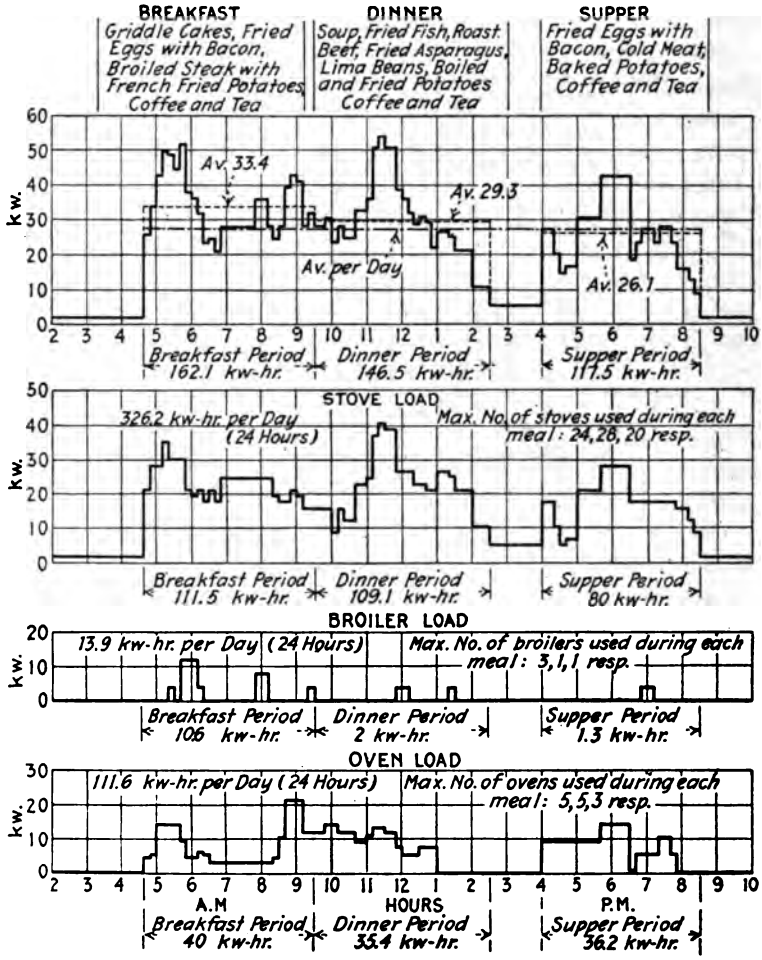

FIG. 2—TRIAL TRIP OF U. S. S. *Texas*

Five ranges, 162 men—energy consumption of electric ranges in officer's galley October 30, 1913. (24 hr.) 451.7 kw-hr.—coffee and tea are kept hot at all hours.

ranges were in actual use in the preparation of this meal. The load factor, taking it as the ratio of the average to the maximum demand, was, therefore, about 50 per cent. The ratio of the maximum demand to the connected load (used) was 54 to 120.

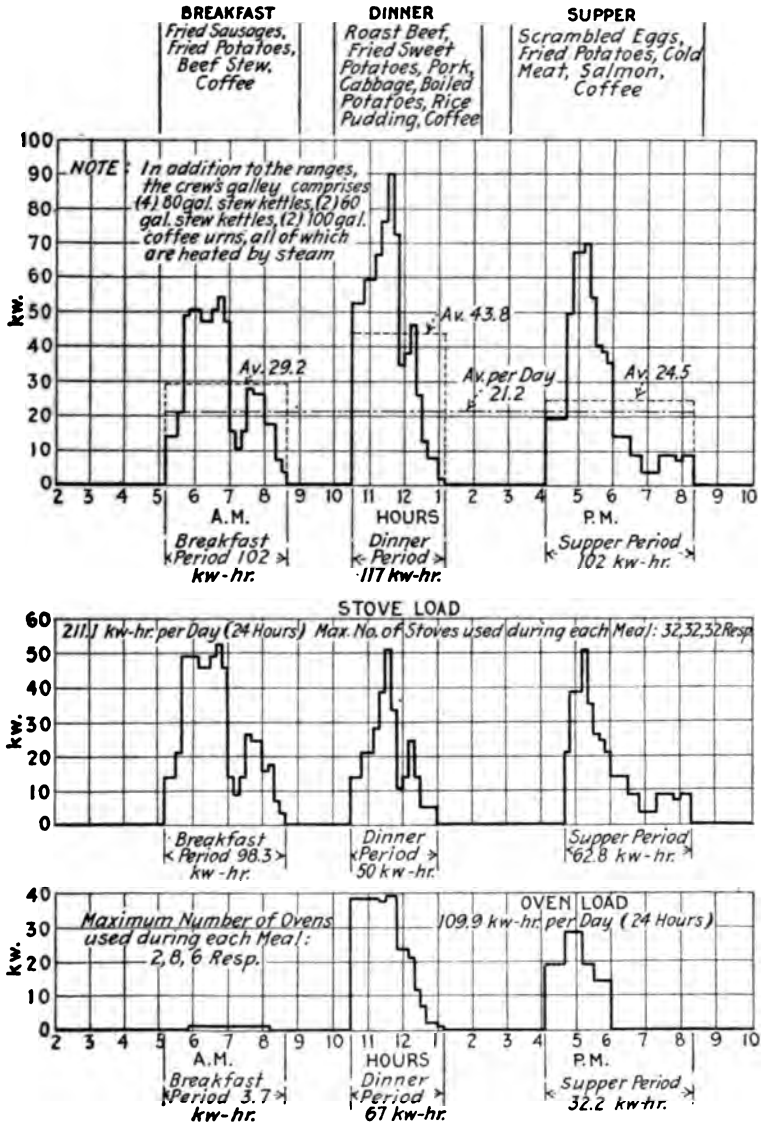

FIG. 3—TRIAL TRIP OF U. S. S. *Texas*

Ten ranges, 553 men—energy consumption of electric ranges in crew's galley October 29, 1913, (24 hr.) 321 kw-hr.

The curves in Fig. 3 show a daily load curve for the ranges in the crew's galley indicating a total consumption of 321 kw-hr. The average demand was only 21.2 kw. and the maximum was 90 kw. (during the dinner period), making a load factor of about 24 per cent. Though there are ten ranges installed, only eight ranges were in use, making a total connected load of 240 kw-hr.; but, judging merely from the number of hot plates used that day, only four ranges were necessary. The ratio of the maximum demand to the connected load was, therefore, 90 to 240; whereas if it had been possible for the cooks to operate so as to use each range at its maximum, the ratio would have been 90 to 120.

It will be interesting for comparison here to note that the total electric load of the *Texas* is about 600 kw.

The kilowatt-hour curve shown in Fig. 1, covering a period of five days, was taken from wattmeter readings. The other curves were computed by taking ten-minute readings throughout the period of the number of hot plates, ovens, etc., that were in use at each time.

The range used on the *Texas* consists of a cooking surface composed of eight rectangular hot plates having a total useful area of 37 by 24 in. (0.93 by 0.6 m.). Directly under the cooking surface are the two broilers 18 by 24 in. (0.45 by 0.6 m.). Below the broilers are two roasting ovens each of which is 18 by 28 by 16 in. (0.45 by 0.71 by 0.4 m.). Each hot plate takes 1750 watts maximum; each broiler, 4000 watts, and each oven 4800 watts, maximum. The total connected load of the range is, therefore, 31.6 kw. One range oven will roast 75 lb. (34 kg.) of meat at one time.

The bake ovens have a consumption of 16 kw. maximum and a capacity of about 100 loaves.

An important point is that all heating elements of the cooking apparatus are readily replaceable.

Advantages of Electric Cooking

We shall now sketch briefly an outline of the conditions on board ship which we expect to see realized in the near future.

Compared with the old-fashioned, coal-burning, brick oven, the electric oven shows a most decided advantage. The electric oven will require only two-thirds the time to be heated up to baking temperature. The only effort required from the baker being a turn of the switch, his time and energy, therefore, can be entirely devoted to its proper purpose,—baking good bread for

passengers or crew. And we must not forget that he will be further aided by motor-driven dough kneaders and other modern bake shop conveniences. There will be no excuse for slack-done or over-done bread or no excuse for stale bread or lack of bread,—as the electric oven will need no attention but an occasional turning of the switch to " high," " low " or " medium " as may be required. The electric oven will not demand any shifting of the loaves in the oven to give some of them the advantage of a hotter place or relieve others from burning, a matter which not only dissipates the cook's time and attention but also considerable heat while the doors are open. Furthermore, one electric oven will do the work of two coal ovens and with more than a corresponding saving in space and a very much greater saving in weight.

The temperature of the bakery will not be appreciably increased as formerly from the waste heat of the radiating brick of the coal oven and the baker's temper and his bread should be as good in the tropics as in the arctics.

What has been said regarding the ship's oven also applies with similar force to the ship's range. Here the compartment previously devoted to the fire and ash box is devoted to an extra roasting oven, increasing the roasting capacity 100 per cent, besides adding special broiling space which provides for two broiling compartments. There is not, of course, much opportunity of increasing the utility of the range top, all of which was formerly active as a cooking surface.

Saving space formerly required for coal boxes, eliminates fuel or ash handling and, therewith, danger from fire or explosion. Absolutely uniform temperatures are secured by the electrical method.

One of the chief advantages in the electric range lies in the broiler, which the coal range entirely lacked. Broiling, like toasting and similar operations, requires a very high degree of heat which should be in the nature of radiated heat from a red hot source; lower temperatures will give the effect of roasting or baking. The coal range often has been the despair of the cook when he wished to do broiling, for that operation required just the right condition of the coals, which is difficult, if not impossible to secure when desired; but the " electric " cook simply turns the switch and instantly the electric coils glow with radiant heat and the sizzling steak at once responds to the broiling operation. Broiling in the coal range also interfered seriously with other

cooking on the stove top. The broiler will also often be useful in browning the products of the oven and, indeed, will be used as a toaster.

The appliances we have described are chiefly used for what we may call high temperature cooking operations—broiling, toasting, roasting, baking, frying, grilling, rapid boiling, etc.—and, of course, it is in this direction that electric cooking finds its greatest advantages.

There will be considerable reduction in the depreciation cost of high temperature cooking appliances, as it will no longer be necessary to renew fire boxes, etc., or oven linings and stove tops, because the electric ranges will not *overheat*.

Advantages of Electric Heating

The problem of heating staterooms, cabins and saloons by electric heating will be solved by two general forms of heaters, both having the same advantage of perfect control and both effecting a saving in space and weight over that taken by the old style steam piping, not to speak of the absence of leaking, sizzling and pounding steam. Furthermore, there is an advantage in low initial cost, as well as in installation and maintenance cost, besides the feature of portability. This feature not only adds to convenience, but may often enhance the warmth and comfort of the occupants of a room. One of the most important advantages, however, lies in being able to regulate the amount of heat desired, accommodating atmospheric conditions or personal requirements. Overheated atmosphere may be worse than cold and an open window or porthole impractical if not risky.

The two methods are the direct air heating and the luminous. The former is especially adapted to the heating of larger spaces where the air can be circulated over electrically heated coils at moderate temperatures. The ideal electric air heater will have a low operating temperature and a large radiating and proper deflecting surface; the former to avoid any fire risk and the latter to produce a more uniform distribution of heat throughout the room by heating to a less degree a larger amount of air at one time, and to more effectively heat the lower strata of air. The method of heating, itself, is precisely that of the old steam radiator without, of course, any disadvantages already referred to.

The other form of air heating, the luminous method, can only be safely secured on shipboard by electric means. This has the advantage, but none of the drawbacks, of the cheerful glow of the

open fireplace, or the comfort of the sun bath. The radiated heat energy does not heat the air directly, but passes through it, giving up its genial warmth to the material object it strikes. The luminous radiator gives its maximum heat instantly upon the turn of the switch. Indirectly, of course, the atmosphere will gradually become heated from its use, but *instantly* a person may be warmed by coming within the range of its glow. It is, therefore, the ideal heater for the stateroom or the bathroom and for auxiliary use in the larger gathering places.

The luminous radiator will, undoubtedly, consist of a specially made incandescent lamp as a heating element; designed, however, for low *luminous* efficiency but for high *thermal* efficiency, emitting a large percentage of infra-red radiations.

Other Electrical Accessories

Perhaps a word should be said in passing for the electric flat iron in the laundry and the soldering iron in the repair shop, because as a matter of fact these are in general use and their convenience and success have really been an entering wedge for the adoption of electric cooking and other electric heating on shipboard. On the therapeutic side, the ship's surgeon will find in the electric hot water supply, the instrument and bandage sterilizer, and body heating pad, convenient aids.

Conclusion

In conclusion, it is our belief that all the handling of fires, of coal and ashes or oil, if done at all, should be done where it belongs, down below in the boiler room, not in the galley; and by the stoker, not by the cook. A contented state of mind, whether on the part of passengers or crew, is highly desirable on shipboard; and when the electric cooking has become generally adopted on shipboard, this will be largely assured through well and more easily cooked meals.

DISCUSSION ON "THE FUTURE OF ELECTRIC HEATING AND COOKING IN MARINE SERVICE," (MAUGER), NEW YORK, MAY 19, 1914.

W. S. Hadaway: In reading this paper of Mr. Mauger's, the first omission that strikes me is the practical elimination of the electric laundry on board ship. It has been my experience that the adoption of electrically heated laundry machines, such as body ironers, combination ironers, as well as hand irons, is an essential part of the equipment for the comfort of the men on an extended cruise.

When it comes to electric cooking my opinion is that the problem is not as simple, and that the solution is not as complete, as would be indicated by the results stated in this paper. I think I can say that the paper is based largely on the trial trip of the *Texas*, plus a considerable amount of optimism.

As I recall the specifications used by the department, they were put out in 1910, and bids for apparatus have been asked for under them several times. The contractors who have bid under these specifications thus far have had to pay very dearly for their experience.

So far as the oven is concerned, the electric range can be made a complete success. I want to call your attention, however, to the fact that the ovens referred to there are equipped for an input of 1 kw. per cu. ft., which is an extremely high input, considering the input which well-insulated ovens are figured to have. My information shows that the average oven in the market runs more nearly 0.8 kw. than 1.00 kw. per cu. ft.

When it comes to the broiler, I believe the author is entirely correct in saying that the present radiant unit for broiling and toasting is entirely satisfactory. The only point where the electric range falls down, and falls down good and hard, is on the top surface cooking.

You will note that useful area for top surface cooking is given approximately as 37 by 24 in. It is my understanding that these top surfaces are made up of a series of eight plates, each of which is 9 by 12 in. On the basis of an input of 1750 watts per plate, this would make the input per square inch approximately 18 watts. It has been the result of experience that a density of 18 watts per square inch represents approximately only one-half the rate of work which can be obtained by the ordinary coal range. Furthermore, the temperature at which the electric hot plate works is so low, compared to the coal range, that the service obtained from the electric range is wholly unsatisfactory.

My own experience in this line of work dates back to 1894, twenty years ago this summer, when we made an installation on the receiving ship *Vermont*, then lying at the Brooklyn navy yard. At that time the galley attendants were all Japanese, and the ingenuity which they showed in their endeavor to

make that stuff work was amazing. They wanted it, but they could not get the work out on time, and we had to take the apparatus out.

The same sort of an equipment was in use for about eighteen months after that installation had been made, in the offices of the manufacturing company, and wattmeter readings of the work done were kept, as well as records of the number of people served, and it was found that the input per person per meal was somewhat less than the figures given by the author.

As to my experience with the electric cooking proposition, I would say that there is no doubt as to the perfect success of the electric baking oven. I call attention, however, to the Navy specification which permits a loss of 40 watts per square foot, indicating heat insulation values which are relatively low—in fact, so far as I have data at hand for the moment, somewhat lower than we obtain in average practise.

The future of this work, it seems to me, is based solely on whether we can devise a durable structure that will do top surface cooking, such as frying, boiling, in small utensils, in a manner which will approach the results obtained on the older types of apparatus. It is too much to expect to get chefs, or people of that order of intelligence, to change the method of use. We have got to supply heat in relatively large volumes at high temperatures and make the apparatus speedier. The development of the chrome-nickel resistor makes this possible. The difficulty in doing it, however, is the added load which we place upon the generator plant. In other words, if we raise the top surfaces up to the point where they would compare directly with the coal range, we would increase the watt capacity, the connected capacity of the range, from 31.6 to 45.6 kw.

E. F. Dutton: There is one point I think should be considered, and that is the quality of the baking. It has been the experience, I understand, on shipboard, that the product is so much better, and the waste is so much less, that this fact goes very far toward overcoming other apparent disadvantages of the electric cooker.

Of course, the first thing that is spoken of in looking at a galley is the cleanliness of the galley, and that is one of the inherent advantages of the electric range or oven.

H. J. Mauger: I think Mr. Hadaway's remarks are very much to the point, and he, like ourselves, would like to have hot plates that would be more rapid. I think, however, Mr. Hadaway has kept that figure of watts per square inch in his mind more than is necessary. I remember a paper that he read before the American Institute of Electrical Engineers some time ago in which he brought out the fact that a gas flame would develop 40 watts per square inch, whereas up to that time the usual hot plate that it was safe to design consumed around 10 watts per square inch. But in a coal range

n board ship the cooking top does not become equally hot. t is only over the coal box that it is hottest, and we have not ound any complaint from the cooks on the score that Mr. Iadaway points out, that the cooking is any slower than by he coal method. Even with only 16 watts per square inch, it eems to be satisfactory for present purposes, and there are evelopments in the art which will soon enable us, doubtless, o go beyond that.

Mr. Hadaway referred to the development of the chrome-ickel alloy, which gives a remarkably fine resistor, but it is the application of that resistor that we find our practical nitations. We have got to insulate that resistor electrically ith something, and the thing usually used is mica. Mica hydrates and breaks down at around 700 to 800 deg. cent., pending on the quality and the character of the mica, so at makes a limitation in that direction; one that prevents our erating at a higher temperature. But I think that when e hot plates are applied as in the range the heat is drawn om more than one plate into the vessel in which the cooking being done, each hot plate contributing its heat—and in that ay makes up for any theoretical lack in watts per square inch ider the vessel, so that the cooks seem to be able to get the me results as with coal or gas.

Doubtless on the question of thermal insulation much can done and much more will be done. I might say that there a domestic range just recently on the market, having an oven hich has remarkable thermal insulation, in which the current cut down to about half of what was formerly required. How-er, the larger the apparatus, the less relative radiating surface ere is in proportion to the power that is used, so that the estion of saving a few watts is not so important as it is when u are trying to cook in your own kitchen, at the lighting rate, ithin the means of your pocket-book.

Frank T. Leilich: The advantages of electric heating and oking as set forth by Mr. Mauger can hardly be questioned. owever, when viewed from the standpoint of cost, such plications of electricity can hardly be said to possess obvious lvantages.

Aside from the illogical procedure of converting the heat ergy of fuel into mechanical energy which is in turn con-rted into electricity and this finally transformed into heat, e electric range and oven are open to the following very rious objections:

1. High first cost.
2. High cost of repairs.
3. High operating cost.

he first and second objections may become less serious in ew of possible improvements in manufacture of the apparatus. rom the present outlook the third will, however, become of ill greater importance than at present, owing to the increasing ice of fuels.

As a matter of fact the fuel oil range is coming forward as a most serious competitor of the electric apparatus. The former combines relative cheapness of first cost with low cost of operation and ease of control. On the Pacific coast there are in operation a number of highly successful installations of oil ranges. Low pressure oil delivery is used in most instances. The most serious objection to oil is the fire risk, but with reasonable care and a well-designed installation the danger becomes a secondary factor.

The best steam plants convert not over about 16 per cent of the heat energy of fuel into electricity, and with the Diesel engine, the most efficient prime mover known, not more than about 30 per cent can be converted. It does not seem unreasonable to suppose that an oil range can be made in which at least 40 per cent of the heat of combustion is available at the heating surfaces.

Assuming a ship with a crew of 1000 men and taking Mr. Mauger's estimate of 1.25 kw-hr. per man per day as the requirement for electric cooking, the daily costs of electric and oil operation would be about as follows

1250 kw-hr. of electricity at 1.0 cent .....$12.50.
83 gal. of oil at 4.5 cents .....3.74.

The oil consumption is based on 40 per cent efficiency of the range and a B.t.u. requirement per day per man equivalent to that produced by 1.25 kw-hr. The heating value of the fuel was taken at 18,000 B.t.u. per pound.

If repairs and investment costs are considered, the oil range will make a still better showing than indicated by the above figures.

Presented at the Seattle Section meeting of the American Institute of Electrical Engineers, Seattle, Wash., May 19, 1914.

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EFFECT OF ELECTROLYSIS ON THE COMPRESSIVE STRENGTH OF CEMENT AND CONCRETE

BY C. EDWARD MAGNUSSON AND B. IZHUROFF

ABSTRACT OF PAPER

A paper on "The Electrolytic Corrosion of Reinforced Concrete", by C.E. Magnusson and G. H. Smith, was read before the A. I. E. E. June 30, 1911, and, as stated in that paper, the results could not be pronounced entirely conclusive, as the duration of the experiments was only 30 days. In the present paper a similar series of experiments is described by the authors in which the tests were continued for several months. The paper gives in tabular form the results of a large number of experiments and the conclusions corroborate the results reported in the former paper.

For the current density covered by the experiments, the current was found to produce no change in the compressive strength of concrete cubes, from which it is deduced that the failures of reinforced concrete due to electrolysis are due entirely to the forces produced by the increase of volume when iron is changed into iron oxide, and not by any direct action of the current upon the concrete.

THE results of a preliminary test made in 1911 on the effect produced by an electric current on the compressive strength of cement and concrete were included in a paper on "Electrolysis in Reinforced Concrete."* As stated in that paper, the experiments were of too short duration, thirty days, to make the results conclusive. In order to secure more evidence a new series was begun in September, 1912. The method used was essentially the same as in the preliminary series. A better means for keeping the cubes moist was devised; also, by tightly wrapping the cubes with rubber and friction tape, practically all the leakage was eliminated, so that all of the current in each circuit passed through the four cubes in series.

Unless exception is noted the following conditions will apply:

(1) The cement used was of the "Washington" brand, manufactured at Concrete, Washington. This brand is of good commercial quality, and is used extensively in the Puget Sound region. The tensile strength complies with the specifications for Standard Portland cement, as given by the American Society

*A. I. E. E. TRANS. Vol. XXX, p. 2055.

for Testing Materials. Chemical analysis and physical test data for this cement are given in Table 1.

TABLE I

Chemical analysis and physical test of the cement.

SiO_2	21	per cent
AlO_3	7	per cent
Fe_2O_3	2	per cent
CaO	66.5	per cent
MgO	1	per cent
SO_4	0.5	per cent
Na_2O and K_2O	2	per cent
Specific gravity		3.12

Fineness:—

Weight of sample	50.0 gr.		
Aver. of 3 samples: retained on 200 mesh	7.9 gr.,	14	per cent
" " 100 "	0.29 "	0.58	per cent
" " 50 "	0.02 "	0.04	per cent
Normal consistency 400 gr. cement 88 gr. water	21.6	per cent	
Penetration	10.5		

Tensile Strength:—

Aver. of 3 samples: 24 hours	108 lb.
7 days	499 "
28 days	717 "

(2) The "fresh water" used was from Cedar River; the data from a chemical analysis and specific resistance are given in Table II.

TABLE II

Chemical analysis of Cedar River water expressed in milligrams per liter.

Nitrics	0.0
Nitrates	0.0
Free ammonia—a trace	
Albumenoid ammonia	0.0
Free oxygen	0.8
Chlorine	3.5
Total solid	41.0
Fixed solid	21.0

Electrical conductivity per cm^3	at 20 deg. cent.	at 30 deg. cent.
Cedar River water	20,100 ohms	15,600 ohms.
Fifth normal NaCl solution	54.4 "	45.4 ".

(3) The "salt water" used was a 3 per cent NaCl solution in Cedar River water.

(4) Natural sand, screened to pass a sieve having 20 meshes per linear inch and retained on a sieve having 30 meshes, was used.

(5) The gravel was screened to pass a sieve having 4 meshes per linear inch, and retained on a sieve having 8 meshes.

Two hundred and forty 2-inch (5-cm.) cubes were made as follows:

(a) Sixty cubes of cement with "fresh water."

(b) Thirty-six cubes of mortar with "fresh water."

Ratio of cement to sand, 1: 3.

[MAGNUSSON AND IZHUROFF]

FIG. 1—ARRANGEMENT OF TEST APPARATUS

(c) Twenty-four cubes of concrete with "fresh water."
Ratio of cement: sand: gravel = 1: 1: 1
(d) Sixty cubes of cement in "salt water."
(e) Sixty cubes of concrete in "salt water."
Ratio of cement: sand: gravel = 1: 1: 1

The cubes were made in accord with the specifications of the Committee on Uniform Testing of Cement, American Society of Civil Engineers.

Six bronze molds were used and six cubes were made at a time, and in the tables this is termed a "set." In making the cubes due care was taken to secure uniform conditions. The consistency was adjusted to give a reading of ten on the scale of a Vicat needle. The cubes were kept in the molds, under cover of a damp cloth to keep the air moist, for 24 to 28 hours.

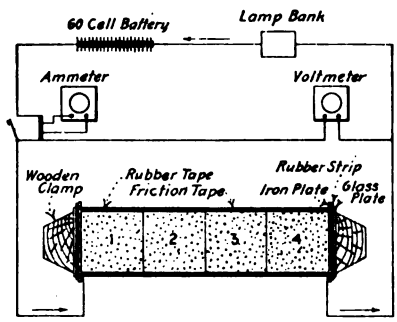

FIG. 2

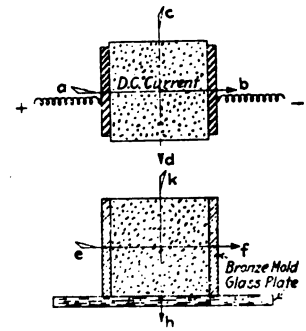

FIG. 3

At removal from the molds each was numbered, and then immersed in water, "fresh" for groups (a), and (b), and (c), and "salt" for (d) and (e), where they were kept for forty to sixty days, as recorded in Tables VII to X.

Four cubes from each set were then placed in the electric circuit; No. 1 nearest the anode, next No. 2 and No. 3, with No. 4 nearest the cathode. The remaining two cubes, No. 5 and No. 6, were kept in the water as control. As the four cubes in the electric circuit were kept moist throughout the experiment, the only factor affecting cubes No. 1-4 more than No. 5-6 would be the electric current passing through the former.

The arrangement of the cubes and the wiring is shown in Fig. 2. At each end an iron plate was placed, extending a little beyond the surface of the cubes, and having a copper wire soldered to one edge for electrical connection. A glass plate

and a rubber strip were placed outside the iron for insulation and the whole secured by a wooden clamp. By means of this clamp, pressure could be applied so as to give a fairly good contact between the iron plates and the cubes, and also to bring the four cubes into close contact. The sets were wrapped tightly with rubber tape, and this secured by friction tape. In order to keep the cubes moist small openings were made through the tape on top of the cubes. These openings were covered by inverted test tubes, full of water, salt or fresh, according to which had been used in making the cubes. See Fig. 1. Absorbent cotton was placed under the test tubes and in this way the water could slowly seep through the cotton and keep the cubes moist. A storage battery of 60 cells in series with a lamp bank was connected to the iron plates. The voltage was applied continuously.

The currents in the circuits were characteristically irregular.

The iron plates corroded at the anode ends of all the sets. In the salt water sets the corrosion was much more rapid than with the fresh water cubes. The cotton under the test tubes near the anode became saturated with the iron oxide. In the salt water sets the discoloring appeared in a few hours, while with the fresh water three or four days were required. In set No. 7 the cotton was colored a greenish blue or Fe_3O_4 while all the rest showed the red color of Fe_2O_3.

No odor was noticeable from the fresh water cubes. The chemical reactions probably consist simply of a decomposition of water and the formation of iron oxide.

$$3H_2O \longrightarrow 6\,H + 3O$$
$$3O + 2\,Fe \longrightarrow Fe_2O_3$$

No tests were made to determine a possible migration of sulphates and other salts.

An odor of chlorine accompanied the reactions in the salt water sets. The following equations give the main reactions:

$$4\,NaCl \longrightarrow 4\,Na + 4\,Cl$$
$$4\,Cl + 2\,H_2O \longrightarrow 3\,H\,Cl + H\,ClO + O$$
$$H\,Cl\,O \longrightarrow H\,Cl + O$$
$$2\,Fe + 3O \longrightarrow Fe_2\,O_3$$
$$Fe_2O_3 + 6\,H\,Cl \longrightarrow 2\,Fe\,Cl_3 + 3\,H_2O$$

The chlorine odor indicates the presence of hydrochloric acid and this may cause a secondary reaction that might affect the crushing strength of the cubes.

TABLE III

Compressive strength of cement cubes made in fresh water.

Cube Nos.		Direction of crushing	Compr. str. in pounds.	Compr. str. lb. per sq. in.	Compr. str. kg. per cm.²
	1	ab	48,580	12,145	851
	2	ab	47,380	11,845	832
	3	ab	38,950	9,737	684
Set No. 1	4	ab	49,000	12,250	860
	5	kh	42,720	10,680	750
	6	kh	53,570	13,392	940
	1	cd	43,040	10,760	756
	2	cd	46,980	11,745	824
	3	cd	43,630	10,907	765
Set No. 2	4	cd	40,160	10,040	704
	5	ef	36,650	9,163	644
	6	ef	50,770	12,693	890
	1	ab	35,720	8,930	626
	2	ab	39,870	9,967	700
	3	ab	35,220	8,805	618
Set No. 3	4	ab	35,020	8,755	615
	5	kh	40,650	10,162	713
	6	kh	31,840	7,960	559
	1	cd	30,530	7,630	535
	2	cd	38,190	9,548	670
	3	cd	29,290	7,323	514
Set No. 4	4	cd	35,430	8,857	622
	5	ef	29,350	7,337	515
	6	ef	24,730	6,183	434
	1	ab	35,250	8,812	619
	2	ab	40,240	10,060	706
	3	ab	30,700	7,675	539
Set No. 5	4	ab	34,630	8,657	607
	5	kh	38,000	9,500	667
	6	kh	28,730	7,183	503
	1	cd	31,740	7,935	556
	2	cd	39,350	9,837	690
	3	cd	43,550	10,888	765
Set No. 6	4	cd	40,340	10,085	707
	5	ef	30,470	7,618	535
	6	ef	45,560	11,390	800
	1	ab	41,760	10,440	734
	2	ab	35,140	8,785	616
	3	ab	36,030	9,008	633
Set No. 7	4	ab	44,290	11,072	778
	5	kh	40,000	10,000	702
	6	kh	29,750	7,438	522
	1	cd	45,770	11,443	801
	2	cd	35,520	8,880	623
	3	cd	38,640	9,660	678
Set No. 8	4	cd	34,510	8,627	605
	5	ef	40,050	10,012	704
	6	ef	46,380	11,595	813
	1	ab	41,660	10,415	730
	2	ab	42,920	10,730	752
	3	ab	41,355	10,339	725
Set No. 9	4	ab	44,440	11,110	779
	5	ab	47,050	11,762	827
	6	ab	42,140	10,535	740
	1	cd	32,800	8,200	576
	2	cd	40,480	10,120	710
	3	cd	43,775	10,944	768
Set No. 10	4	cd	42,450	10,612	744
	5	ef	39,160	9,790	687
	6	ef	40,760	10,190	715

TABLE IV

Compressive strength of concrete cubes in fresh water.

Cube Nos.		Direction of crushing	Compr. str. in pounds.	Compr. str. lb. per sq. in.	Compr. str. kg. per cm.²
	1	ab	5,470	1,363	96
	2	ab	5,430	1,358	95
	3	ab	5,780	1,445	102
Set No. 11	4	ab	4,000	1,000	70
	5	kh	5,090	1,273	89
	6	kh	7,340	1,835	129
	1	cd	6,800	1,700	119
	2	cd	6,685	1,671	117
	3	cd	6,800	1,700	119
Set No. 12	4	cd	7,820	1,955	137
	5	ef	6,260	1,565	110
	6	ef	8,000	2,000	141
	1	ab	6,360	1,590	112
	2	ab	9,120	2,280	160
	3	ab	9,290	2,323	163
Set No. 13	4	ab	10,390	2,592	183
	5	kh	10,100	2,525	178
	6	kh	7,810	1,952	137
	1	cd	8,980	2,245	158
	2	cd	10,000	2,500	176
	3	cd	10,830	2,707	190
Set No. 14	4	cd	11,760	2,940	206
	5	ef	8,010	2,003	141
	6	ef	11,000	2,750	193
	1	ab	5,500	1,375	97
	2	ab	5,750	1,437	101
	3	ab	5,670	1,418	99
Set No. 15	4	ab	7,740	1,935	136
	5	ab	5,590	1,398	98
	6	ab	6,000	1,500	105
	1	cd	13,480	3,370	237
	2	cd	8,900	2,225	156
	3	cd	12,210	3,042	214
Set No. 16	4	cd	8,970	2,243	158
	5	ef	10,680	2,670	188
	6	ef	11,570	2,892	203
	1	ab	14,300	3,575	251
	2	ab	12,220	3,055	215
	3	ab	11,840	2,960	208
Set No. 17	4	ab	10,810	2,703	190
	5	kh	12,390	3,098	217
	6	kh	10,530	2,632	185
	1	cd	14,470	3,618	254
	2	cd	18,650	4,662	328
	3	cd	17,380	4,345	305
Set No. 18	4	cd	16,740	4,185	294
	5	ef	14,080	3,520	247
	6	ef	12,250	3,063	215
	1	ab	12,900	3,225	226
	2	ab	19,590	4,897	344
	3	ab	19,860	4,965	349
Set No. 19	4	ab	19,470	4,868	342
	5	ab	16,230	4,058	286
	6	kh	19,760	4,940	347
	1	cd	12,370	3,092	217
	2	cd	14,230	3,557	250
	3	cd	9,850	2,463	173
Set No. 20	4	cd	12,980	3,245	228
	5	ef	13,860	3,465	243
	6	ef	13,170	2,392	231

Testing Cubes

Finally, the cubes in the electric circuit and the controlling cubes were tested for their compressive strength, using a Riehle 60,000-lb. testing machine. All cubes were tested under as nearly identical conditions as possible, using the same machine and at the same speed. In Tables III to VI inclusive are recorded the crushing strength of all the cubes tested. Numbers 1, 2, 3, 4 in each case have been in the electric circuit. One-half of the tested cubes were crushed in the direction of the flow of the current, and the other half were tested in direction perpendicular to the flow of the current. One-half of the control cubes were crushed in the direction of the open ends of the bronze mold and the other half in the direction of the sides of the mold. In Fig. 3 and in Tables III to VI, the corresponding directions with letters are given. In Tables VII to X inclusive are given the data for each set.

Summary

(a) The compressive strength of fresh water cement cubes was not affected by an average current density of 1.2 milliamperes per square inch (0.17 milliampere per cm^2) applied for 310 days. Tables III and VII.

(b) The compressive strength of fresh water concrete cubes was not affected by an average current density of 1.8 milliamperes per square inch (0.26 milliampere per cm^2) applied for 225 days. Tables IV and VIII.

(c) The compressive strength of salt water cement cubes was probably not affected by an average current density of 10.2 milliamperes per square inch (1.4 milliampere per cm^2) applied for 113 days. Tables V and IX.

(d) The compressive strength of salt water concrete cubes was not affected by an average current density of 13.8 milliamperes per square inch (1.9 milliampere per cm^2) applied for 110 days. Tables VI and X.

For (a), (b), (d) the average values for the cubes treated with the electric current were 1, 2, 3.0 and 2.5 per cent respectively, stronger than the corresponding control cubes. For group (c) the cubes in the electric circuit were 14 per cent weaker than the control. An examination of the crushing strengths in Table V will show that the apparent decrease is most likely due to a chance selection of too many of the stronger cubes for the control. If any action were due to the current the liberated

TABLE V

Compressive strength of cement cubes made in salt water.

Cube Nos.		Direction of crushing	Compr. str. in pounds.	Compr. str. lb. per sq. in.	Compr. str. kg. per cm.²
Set No. 21	1	ef	34,400	8,600	604
	2	ef	33,845	8,461	595
	3	ef	31,900	7,975	561
	4	ef	27,140	6,785	475
	5	ef	39,305	9,828	690
	6	ef	40,510	10,128	712
Set No. 22	1	kh	19,570	4,893	344
	2	kh	30,610	7,652	537
	3	kh	39,355	9,839	690
	4	kh	27,375	6,844	480
	5	kh	39,540	9,885	694
	6	kh	38,710	9,678	679
Set No. 23	1	ab	18,895	4,723	332
	2	ab	27,195	6,799	476
	3	cd	35,790	8,947	627
	4	ab	28,500	7,125	500
	5	ef	34,520	8,630	605
	6	ef	36,450	9,113	640
Set No. 24	1	cd	35,455	8,864	622
	2	ab	22,440	5,610	394
	3	ab	31,970	7,992	560
	4	ab	24,880	6,220	437
	5	ef	37,800	9,450	664
	6	ef	32,400	8,100	568
Set No. 25	1	bd	27,890	6,973	490
	2	ab	29,925	7,324	514
	3	ab	24,510	6,127	430
	4	ab	20,570	5,142	361
	5	ef	41,270	10,318	724
	6	ef	31,720	7,930	555
Set No. 26	1	cd	36,385	9,096	637
	2	cd	34,480	8,620	695
	3	cd	33,270	8,318	584
	4	cd	31,580	7,895	554
	5	kh	37,190	9,297	652
	6	kh	31,330	7,833	550
Set No. 27	1	cd	38,328	9,580	673
	2	cd	34,300	8,575	602
	3	cd	33,325	8,331	585
	4	cd	33,390	8,348	586
	5	ef	36,525	9,131	640
	6	ef	28,250	7,063	496
Set No. 28	1	cd	28,160	7,040	493
	2	ab	22,240	5,560	390
	3	ab	20,550	5,138	360
	4	ab	31,920	7,980	560
	5	ef	36,900	9,225	647
	6	ef	33,780	8,445	592
Set No. 29	1	cd	42,190	10,548	740
	2	cd	35,180	8,795	617
	3	cd	35,720	8,930	626
	4	cd	40,775	10,194	715
	5	ef	35,860	8,965	630
	6	ef	33,220	8,305	582
Set No. 30	1	ab	25,920	6,480	455
	2	ab	25,360	6,340	445
	3	ab	38,030	9,508	667
	4	ab	37,470	9,367	657
	5	kh	36,730	9,183	644
	6	kh	33,355	8,339	585

TABLE VI

Compressive strength of concrete cubes made in salt water.

Cube Nos.		Direction of crushing	Compr. str. in pounds.	Compr. str. lb. per sq. in.	Compr. str. kg. per cm.²
	1	ab	14,230	3,558	250
	2	ab	18,685	4,671	328
	3	ab	24,110	6,027	423
Set No. 31	4	ab	18,675	4,669	328
	5	ef	12,740	3,185	224
	6	ef	20,940	5,235	367
	1	cd	21,550	5,387	378
	2	cd	20,810	5,202	365
	3	cd	16,210	4,052	285
Set No. 32	4	cd	18,870	4,718	331
	5	ef	18,630	4,657	327
	6	ef	21,280	5,320	374
	1	ab	15,540	3,885	273
	2	ab	22,200	5,550	390
	3	ab	20,230	5,056	355
Set No. 33	4	ab	21,340	5,335	374
	5	kh	18,100	4,525	318
	6	kh	22,620	5,655	397
	1	cd	13,385	3,346	235
	2	cd	14,185	3,546	249
	3	cd	14,880	3,720	261
Set No. 34	4	cd	15,930	3,982	280
	5	kh	12,550	3,138	220
	6	kh	14,200	3,550	249
	1	ab	16,220	4,055	285
	2	ab	23,275	5,819	408
	3	ab	25,330	6,332	445
Set No. 35	4	ab	22,380	5,595	393
	5	ef	17,380	4,345	305
	6	ef	21,330	5,332	374
	1	cd	23,325	5,831	410
	2	cd	19,120	4,780	336
	3	cd	19,780	4,945	347
Set No. 36	4	cd	26,690	6,672	468
	5	ef	23,720	5,930	416
	6	ef	24,500	6,125	430
	1	cd	21,900	5,475	384
	2	cd	18,140	4,535	319
	3	cd	18,920	4,730	332
Set No. 37	4	cd	16,120	4,030	283
	5	kh	16,140	4,035	284
	6	kh	18,200	4,550	320
	1	ab	15,565	3,891	273
	2	ab	13,625	3,406	239
	3	ab	11,545	2,886	203
Set No. 38	4	ab	12,370	3,092	217
	5	ef	14,260	3,565	250
	6	ef	13,270	3,318	233
	1	cd	18,170	4,542	319
	2	cd	15,190	3,797	267
	3	cd	17,000	4,250	299
Set No. 39	4	cd	15,670	3,917	275
	5	kh	18,200	4,550	320
	6	kh	14,070	3,518	247
	1	cd	11,030	2,757	193
	2	cd	14,745	3,686	259
	3	cd	15,000	3,750	263
Set No. 40	4	cd	13,630	3,407	240
	5	kh	14,020	3,505	246
	6	kh	13,220	3,305	232

TABLE VII

Average compressive strength of cement cubes made in fresh water.

No. set.	Total days	Hrs. in electric circuit	Aver. volts	Total amp. hours	Av. comp. str. lb. per sq. in. test cubes	Av. compr. str. kg. cm.² test cubes	Av. compr. str. lbs. per sq. in. control cubes	Av. compr. str. kg. cm.² cont cubes	% change in compressive strength
1	435	7500	116	35	11494	807	12036	845	4.5
2	398	7476	116	35	10863	762	10928	767	0.9
3	397	7452	116	35	9114	640	9061	636	+ 0.6
4	370	7452	116	35	8339	585	6760	475	+ 18.7
5	366	7443	116	34	8801	618	8342	585	+ 5.5
6	361	7443	116	34	9086	680	9504	667	+ 1.9
7	360	7442	116	34	9826	690	8710	612	+ 11.7
8	359	7441	116	34	9652	677	10804	758	11.2
9	349	7277	116	34	10648	747	11148	784	4.5
10	345	7276	116	34	9969	700	9990	701	0.2
				Average	9840	691	9720	683	+ 1.2

TABLE VIII

Average compressive strength of concrete cubes made in fresh water.

11	344	7075	116	45	1292	91	1554	109	16.8
12	339	7074	116	45	1756	123	1783	125	1.5
13	311	5245	116	36	2196	155	2238	157	1.9
14	305	5245	116	36	2598	182	2375	166	+ 9.4
15	302	5244	116	36	1541	108	1449	101	+ 6.9
16	301	5243	116	36	2720	191	2781	195	2.2
17	299	5225	116	36	3073	216	2865	201	+ 7.2
18	297	5224	116	36	4202	295	3292	231	+ 27.8
19	296	5223	116	36	4488	316	4499	316	0.2
20	295	5222	116	36	3089	217	3378	237	8.5
				Average	2695	190	2621	184	+ 3.0

TABLE IX

Average compressive strength of cement cubes made in salt water.

No. set.	Total days.	Hrs. in elec. circuit.	Average volts.	Total amp. hours	Av. comp. str. lb. per sq. in. test cubes	Av. compr. str. kg. per cm.² test cubes	Av. compr. str. lb. per sq. in. control cubes	Av. compr. str. kg. per cm.² contr. cubes	% change in compressive strength
21	439	2744	101	80	7955	559	9977	701	—20.2
22	438	2833	91	128	7307	513	9781	687	—25.3
23	435	2760	98	155	6898	484	8872	622	—22.3
24	433	2820	97	132	7172	503	8775	616	—18.5
25	419	2649	92	122	6391	449	9124	640	—29.9
26	418	2703	92	105	8482	595	8565	601	— 1.0
27	414	2711	95	94	8708	612	8097	568	+10.7
28	415	2688	93	99	6429	451	8835	620	—27.2
29	412	2643	91	97	9617	675	8635	606	+11.4
30	411	2639	95	88	7924	556	8761	615	— 9.5
				Average	7689	540	8943	628	—14.0

TABLE X

Average compressive strength of concrete cubes in salt water.

31	412	2663	91	148	4731	332	4210	296	+12.4
32	409	2 64	91	139	4840	340	4899	350	— 2.8
33	403	2665	94	145	4957	348	5090	357	— 2.6
34	403	2642	91	143	3648	256	3344	235	+ 9.1
35	402	2666	94	155	5450	383	4838	340	+12.0
36	401	2667	96	146	5557	390	6027	423	— 7.8
37	401	2642	92	145	4692	329	4293	302	+ 9.3
38	400	2639	91	150	3319	233	3441	242	— 3.5
39	398	2674	93	142	4127	290	4034	283	+ 2.3
40	397	2651	91	149	3400	239	3405	239	0.0
				Average	4472	314	4367	306	+ 2.5

chlorine would be the most likely agent. Since the chlorine is liberated at the positive pole, it would appear at cube No. 1. In sets No. 22 and No. 23, the cube No. 1 was weakest, but in sets No. 27 and No. 29, cube No. 1 was strongest. Moreover, cube No. 1 in set No. 29 was the strongest in the whole series and hence not likely to have been weakened by the current. The series shows less uniformity in strength than the cubes in either (a), (b) or (c).

Averaging the averages for the four groups, the strength of the cubes Nos. 1, 2, 3 and 4 was only 1.8 per cent less than the control cubes Nos. 5 and 6; and this difference is well within the errors of the experiment.

Summarizing the results, we find that for *the current density covered by the experiments* the current produces no change in the compressive strength of the cubes. This is in accord with the preliminary observations in the earlier paper (A.I.E.E. TRANS. XXX, p. 2067).

Within the limits of current density for which these conclusions apply, it follows that failures in reinforced concrete due to electrolysis are due entirely to the forces produced by increase in volume when the iron is changed into iron oxide, and not by any direct action of the electric current upon the strength of the concrete.

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EXPERIENCES WITH LINE TRANSFORMERS

BY D. W. ROPER

ABSTRACT OF PAPER

This paper presents an analysis of the transformer troubles for one year on a system having nearly 15,000 transformers installed. This analysis indicates that about 50 per cent of the troubles traceable to the transformer can be eliminated, with no great expense, by some slight changes in the construction details and some improvements in operating methods.

Reference is made to the Standard Specifications for Line Transformers issued by the Bureau of Standards. An experiment on 1600 transformers with the connection board removed or submerged proved that the connection board above oil was responsible for about 60 per cent of the transformer troubles due to lightning. Curves showing the record of burn-outs of four different makes of transformers are used as a basis for a discussion of the effect of the value placed on continuous service in the selection of transformers.

The results of experiment with improved lightning protection are given, showing how the troubles were reduced by two-thirds. By taking advantage of the results of the two extended experiments, it should be possible to reduce the troubles due to lightning to about 10 per cent or 20 per cent of the troubles heretofore experienced.

WITHIN recent years the line transformer has been developed by the manufacturers into one of the most efficient and reliable pieces of electrical apparatus. It is fortunate for the central station industry that this is the case, as the distributing transformer, next to the meter, is the piece of apparatus nearest to the customer and for that reason its shortcomings would be most readily noticed. While the breakdowns of apparatus or transmission lines in general involve only a very brief interruption to the service, if any, the failure of a transformer generally means an interruption of several hours and especially so if it is located in a sparsely settled region where inter-connection of secondaries is not possible.

That the transformer is a reliable piece of apparatus is evidenced by the fact that last year the total cost of maintenance and repairs of all transformers, on the distributing system with

The experiences of the author on which this paper is based have been gathered during his connection with the system of the Commonwealth Edison Company in Chicago, and it will be understood, unless otherwise specified, that the experiences and records herein mentioned refer to the system of this company. As this distribution system covers about 125 square miles of territory, including sparsely settled suburban districts, as well as thickly settled urban territory, it is thought that the installation may be regarded as fairly typical.

Name Plate

The standard specifications require a name plate, but make no mention as to its location. It is the custom of the manufacturers to furnish a name plate on which the lettering is of sufficient size to be read when the transformer is standing on the storeroom floor, but which is somewhat more difficult to read when the transformer is installed on the pole. Securing the correct number of a transformer is made particularly difficult in the larger sizes of transformers because the name plate is located on the front of the case near the top. This puts the name plate so far from the pole that the lineman must unsnap his life belt in order to get in a position where he can read the name plate. If the *safety first* campaign is to be extended to name plates on transformers, they will be located in such a position and the lettering will be of such a size that a lineman, without risking his life, can read the name plate while the transformer is in position on a pole.

Cases

The standard specifications provide for eyebolts or hooks for handling transformers. The transformers, however, must be handled many times while in the storeroom or in transit from the storeroom to the line. Last year, in Chicago, the number of transformers replaced in order to increase the capacity was equal to the number installed, and the total number handled during the year was over 40 per cent of the number on the lines at the end of the year. Transformers of 5 kw. and smaller capacity comprise over 60 per cent of the total number installed. With the class of help that is used in this work it is very difficult to prevent the men from using the primary or secondary leads as handles. It appears possible for the manufacturers, at no great expense, to fashion the covers of the

smaller sizes of transformers so as to provide a handle on each side that would be somewhat more convenient for the purpose than the primary leads.

No mention is made of terminals on the primary or secondary leads, but such terminals appear to be quite desirable and are furnished by some manufacturers. It has been suggested that terminals should be located just outside of the porcelain bushings with a solid rod through the bushing. If this could be done, the leads would be so short that there would be no temptation to use them as a handle and, in addition, the solid rod sealed into the bushings would absolutely prevent the siphoning of the oil through the leads. In this manner two of the most aggravating petty annoyances in connection with transformers would be eliminated.

Cut-Outs

The specifications require two primary cut-outs to be furnished with each transformer, but make no mention as to the qualities desired in these cut-outs, assuming apparently that any cut-outs supplied by the manufacturer will be satisfactory. This assumption is not warranted by experience. The number of cut-outs replaced in a year exceeds the total number of burned-out transformers, indicating that the cut-outs are a less reliable piece of apparatus than the transformers. On the system under discussion the larger sizes of transformers were operated without cut-outs for several years, as it was found that better service could be given to customers in this manner than with the types of cut-outs which were available.

If a company is buying transformers on specifications, the probabilities are that within a few years there will be transformers on hand made by several manufacturers, and as several makers furnish their own type of primary cut-out with the transformers, the operating company will soon have several types of cut-outs and must keep in stock and furnish to their troublemen a full line of the various sizes of primary fuses for each of the several makes of transformers. It would be a better plan to have the transformer furnished without cut-outs and for the operating company to secure the cut-outs that are found to be best adapted to its purpose, using one type for the smaller sizes, with one or two additional types of cut-outs for the larger sizes of transformers. Enclosed fuses appear to be the only satisfactory type for the sizes above 40 kw. Some of the points that should be included in the specifications for transformer cut-outs are as follows:

(1) They should be capable of opening the circuit of the transformer whether the short circuit occurs when the cut-out is cold or when it is heated, due to the load.

(2) It should be impossible for the plug to drop out due to the jarring of the pole, or to be blown out by blowing of the fuse or by short circuits or arcing in the cut-out.

(3) It should have sufficient distance between terminals so that if the fuse blows in a driving rain or wet snow storm, the current will not leak across the cut-out between terminals and destroy the cut-out.

(4) The plug should be provided with a handle of such size and shape that the cut-out can be readily removed by a troubleman when wearing rubber gloves and when the handle is wet with rain or covered with sleet.

(5) The plug should have a shield of such size and shape that when the plug is inserted on a short-circuited transformer the resulting arc will not cause any injury to the troubleman.

(6) The cut-outs for the smaller sizes of transformer should be designed for the use of metal strip fuses. The fuse-holding parts should be designed so that the fuse can be readily replaced.

Some further attention should also be given to the subject of the metal strip fuses for primary cut-outs. In some parts of the city these fuses corrode badly, reducing the cross-section of the strip so that the fuses will blow on light loads, and without any apparent trouble in the transformer or on the customer's premises. Some experiments are being made with coated fuses which it is hoped may eliminate this trouble.

Connection Boards

The specifications require that: "The ends of the primary coils shall be brought to a convenient connection board of porcelain or other suitable material within the case and so arranged that the primary coils may be put in series or in multiple", and also that: "Sufficient oil shall be furnished to completely immerse core, windings, and connection board."

All of the manufacturers do not agree that the terminal board should be submerged. It has even been contended that the connection board could be so designed and located that the lightning would jump across the terminals of the primary coils or from the primary terminals to the cover before the potential across the terminals of the coils could rise sufficiently high to burn out the coils. In looking for evidence bearing on

this theory it was found that the repair shops had been, for several years, removing the connection boards from all transformers that were re-wound, and that the percentage of troubles on these transformers was less than with new transformers containing connection boards. An investigation was made of all the transformers whose fuses had blown during a severe lightning storm, and signs of arcing at the terminal board were found in a large percentage of the transformers. These facts seemed to indicate that the connection board was the cause of many of the troubles during lightning storms. For the purpose of checking this theory one circuit with a total of about 250 transformers was equipped with transformers having the con-

TABLE III

COMPARATIVE RECORD OF TRANSFORMER TROUBLES DUE TO LIGHTNING, WITH TRANSFORMERS HAVING CONNECTION BOARDS ABOVE OIL AND WITH CONNECTION BOARDS REMOVED OR SUBMERGED.

		Location of connection boards.	
		Above oil.	Removed or submerged.
1. Number of transformers,		9,878	1,648
2. Fuses blown without damage to transformers,	Number	770	56
	Per cent	7.8	3.4
3. Coils burned out,	Number	77	10
	Percent	0 .78	0 .61
4. Connection boards damaged, leads burned off, etc.	Number	36	0
	Per cent	0 .36	0
5. Total classed as burn-outs, sum of items 3 and 4,	Number	113	10
	Per cent	1 .14	0 .61
6. Total cases of trouble, sum of items 2,3 and 4,	Number	883	66
	Per cent	8 .95	4 .01

nection boards removed or submerged. Careful records were kept during the succeeding year, but the results were disappointing, due apparently to the small number of transformers involved in the experiment. Before the following lightning season arrived, additional circuits were provided with transformers having the connection boards removed or submerged, so that the total number exceeded 1600 transformers. The scheme of lightning protection was not changed, so that the only difference between these transformers and those conforming to standard practise was the removal or submerging of the terminal boards. The results of this experiment for the year 1913 are shown in Table III. In this table, under the heading

"fuses blown" are included all cases of trouble which involved blowing of the primary fuse but which left the transformer in operating condition. Under "burn-outs" are included all transformers which were not in condition for service and had to be replaced. The results as shown in this table indicate that the terminal board above oil is the cause of about 60 per cent of the troubles during lightning storms. The results further indicate that the connection board does not act as a lightning arrester in protecting the transformer coils from damage, but on the contrary that a larger percentage of coils is burned out when transformers are provided with such connection boards above oil than when they are removed or submerged.

It appears, therefore, that the standard specifications have taken a long step forward in specifying that the connection boards must be submerged under oil, but as only a small percentage of the transformers that are provided with connection boards are ever used on 1000-volt circuits, it is therefore suggested that a further improvement could be made by requiring that transformers for use on 2000-volt circuits shall be furnished without connection boards and limiting the use of transformers with submerged connection boards to those companies which have 1000-volt distributing circuits.

Oil

The standard specifications require that oil be furnished with the transformers. The situation with oil is somewhat similar to that regarding cut-outs. Each of the several manufacturers furnishes a different type of oil, so that with several makes of transformers in use it would be necessary to keep on hand several kinds of transformer oil and to see that the proper kind of oil was sent out with each transformer. It is possible to obtain a good grade of transformer oil which is entirely suitable for use with all of the several makes of transformers now on the market. Therefore, it appears to be a better practise in purchasing transformers on specifications, to require that they shall be furnished without oil, and to buy the oil separately under proper specifications, provided, however, that the purchaser has suitable facilities for making the necessary tests.

Design, Materials and Workmanship

The standard specifications contain a paragraph reading as follows: "Action upon these features will be based on the

requirements of the specifications and observations made while the apparatus is under test." Later in the specifications, under the head of "Basis for Comparing Guarantees", is a paragraph reading as follows:

In case the proposals offered by different bidders in accordance with these specifications guarantee core losses less than those specified in Table I, each watt of difference shall be evaluated at $0.88 for purposes of comparison. For the same purpose, copper loss shall be evaluated at $0.33 per watt for each watt difference between values specified in Table I and the full-load value guaranteed by the bidder.

An inference that can be readily drawn from these two paragraphs is that having passed the qualifying specifications and having been subjected to a critical examination while the transformer was under test, the several transformers furnished by the various manufacturers are then to be considered of equal value except as to the copper and iron losses, and that the relative value of the transformers submitted by the different manufacturers can then be determined by the process of valuation above described. If this assumption was borne out by experience, then we would expect to find that the percentage of burn-outs of the various makes of transformers from all causes during the period of the year was approximately equal.

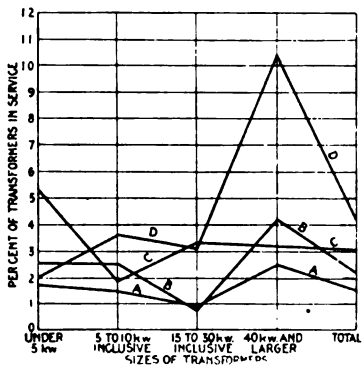

FIG. 1—RECORD FOR ONE YEAR OF TRANSFORMER BURN-OUTS FROM ALL CAUSES.

Each line represents a different make of transformer.

In Fig. 1 are shown the results of a recent year's experience with four different makes of transformers. All of the transformers included in these results have passed tests virtually identical with the qualifying specifications above referred to, but, as shown by the figure, there is a wide range in their ability to withstand the conditions of service. The percentage of burn-outs in service for the best transformer was about one-third of the percentage for the rest. It is, therefore, submitted that it should be possible to devise a specification so that there would not be so great a range in quality of the transformers which have passed the specifications.

In order that the cost of the transformer losses and the cost of repairs of the various types may be shown in their proper

relation to each other, the results shown in Fig. 1 have been applied to the entire installation, assuming that all of the transformers on the system are of each of the several types, and estimates made showing what the total cost of repairs for one year would have been for each of these types of transformers. The iron and copper loss guarantees were also obtained from the same four manufacturers and the total losses for one year were calculated on the assumption that all of the transformers were furnished by each of the several manufacturers. The results of these calculations with different values assumed for the losses and for continuity of service are shown in Tables IV and V. It is not intended that the assumed values should represent the opinion of the author as to the value of these items, but they

TABLE IV

OPERATING COSTS OF FOUR TYPES OF TRANSFORMERS FOR THE YEAR 1913, UNDER ASSUMED CONDITIONS

	A	B	C	D
1. Cost of iron and copper losses at an assumed value of 1.5 cents per kw-hr	$158,600	$148,300	$146,000	$154,000
2. Replacing and repairs	7,700	11,100	14,900	19,800
3. Estimated loss of income, due to burn-outs	265	370	510	675
4. Total of items 1, 2 and 3	$166,565	$159,770	$161,410	$174,475
5. Loss of prestige, (assumed as 15 times loss of income)	3,975	5,550	7,650	10,125
6. Totals of items 4 and 5	$170,540	$165,320	$169,060	$184,600

were assumed over a wide range for the purpose of showing the effect which these values would have in the selection of the best type of transformer for any particular set of conditions. An inspection of these tables shows that the determination by an operating company of the best transformer for its purposes depends upon the values placed by it on the transformer losses and on the continuity of service. If it places a high value on the transformer losses, this feature will determine the best transformer for its purposes. The figures also show that the cost of repairs is a comparatively minor item and that a high value must be placed on continuity of service in order that the savings due to the most reliable transformer may offset the cost of its increased losses.

The Protection of Transformers

Transformers while in service must be protected from overloads and from lightning. It is customary to endeavor to protect against overload by means of primary fuses. In practise, a great many minor troubles occur on the premises of customers which will blow the primary fuses. Such troubles should result in the blowing of the secondary fuses on the premises of the customer and the primary fuses should not blow unless there is trouble within the transformer. To secure this result, the transformer must have primary fuses corresponding to several times its rated capacity, so that a slowly increasing load would burn out the transformer. Protection from overloads is best

TABLE V

Operating costs of Four Types of Transformers for the Year 1913, under Assumed Conditions.

	A	B	C	D
1. Cost of iron and copper losses at an assumed value of 0.5 cents per kw-hr.	$52,860	$49,450	$48,690	$51,500
2. Replacing and repairs,	7,700	11,100	14,900	19,800
3. Estimated loss of income, due to burn-outs,	265	370	510	675
4. Totals of items 1, 2 and 3,	$60,825	$60,920	$64,100	$71,975
5. Loss of prestige, assumed as 15 times loss of income)	3,975	5,550	7,650	10,125
6. Totals of items 4 and 5,	$64,800	$66,470	$71,750	$82,100

secured by proper records and by occasional tests as a check on the records. During the year 1913, the number of transformers burned out by overload was less than one-tenth of one per cent of the number installed. This record indicates the entire feasibility of protecting transformers against overload by means of the records and tests. The primary fuse should therefore be regarded as a device for disconnecting a defective transformer so as to protect the rest of the service, and not for the protection of the transformer itself from overloads.

Protection of distributing transformers against lightning has apparently not received the attention that it deserves. The record of lightning troubles for the year 1913 is shown in Fig. 2. These results show that the larger sizes of trans-

formers are comparatively immune from lightning, and that the greatest number of troubles occur with the smaller sizes, that is, the sizes below 10 kw. The number of transformers of these sizes comprises about 70 per cent of the total installation, so that the transformers which are most susceptible to damage by lightning are the most numerous. It is suggested that careful attention by the manufacturers to the primary bushings, the clearance of the primary leads inside the case, the manner of their support and other minor details, would probably result in a material improvement in these records.

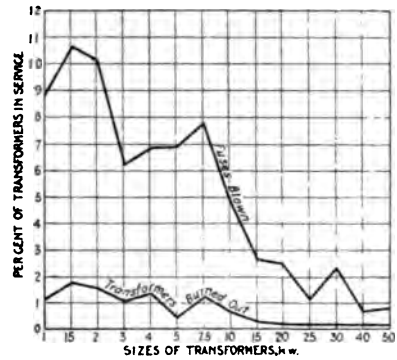

FIG. 2—RECORD FOR ONE YEAR OF TRANSFORMER TROUBLES DUE TO LIGHTNING.

In addition to the experiments mentioned above, which involved the removal of connection boards from a large number of transformers, some further experiments were made in another area, which consisted in

TABLE VI

RECORD OF TRANSFORMER TROUBLES DUE TO LIGHTNING, SHOWING THE IMPROVEMENT IN SERVICE DUE TO THE INCREASED LIGHTNING ARRESTER PROTECTION.

		Ratio of arresters to transformers	
		40 per cent	100 per cent
Location of arresters.		On line poles.	On transformer poles.
Number of transformers,		9,878	1,560
Fuses blown,	Number	770	85
	Per cent	7.8	5.5
Transformers burned out,	Number	113	6
	Per cent	1 .15	0 .39

NOTE: All transformers had connection boards above oil.

installing lightning arresters upon the same pole with each of a large number of transformers. The remainder of the distributing system in question is protected by arresters not located

on the transformer poles but scattered over the lines at a distance of about two thousand feet, resulting in a ratio of arresters to transformers of about 40 per cent. The results of these experiments are shown in Table VI.

In that portion of the territory where there was an arrester on the same pole with each transformer, the results to date as compared with the older practise indicate that the percentage of transformers burned out by lightning is reduced by about two-thirds. The several experiments indicate that by the combination of the two schemes and possibly by some further improvements in some details of the transformers and in the design of the lightning arresters, there should be no great difficulty in reducing the percentage of cases of trouble due to lightning to one-fifth, and possibly to one-tenth, of those experienced in former years. It is hoped that more definite and complete information on this subject may be available within another year.

under any reasonable operating conditions, out of tens of thousands of such transformers in service.

The location of the terminal board will depend largely upon the design of the transformer, the clearances available and the operating stresses which may have to be met. For distributing voltages considerably higher than the 2200-volt classes referred to in this paper, I do not believe that it would be advisable to have a connection board at the oil level. This, for example, would apply to 6600-volt, high-tension distributing transformers. With such transformers, the clearance distances, as well as the terminal board itself, would have to be too large, requiring much more space than is necessary to effectively apply the same on transformers of lower voltage.

After all, the most desirable development would be the elimination of a high-tension terminal board, and that brings up the question of voltage standardization. It is very desirable from many standpoints that voltages and taps should be standardized. On these small transformers, where continuity of service is to be a criterion, multiple voltages and extra taps should be eliminated wherever possible and one of the main functions of the terminal board will be automatically eliminated. It would therefore be very desirable to adopt single voltages on distributing transformers on the high-tension side, where, of course, such simplification is more important than on the low-tension or secondary side.

With a single high-tension voltage, the terminal board could most successfully be replaced with porcelain spacers approximately at the oil level, to provide the desirable support for the leads, without impeding the circulation of the oil, and keeping the high-tension spacer separate from the low-tension board, so that there would be less possibility of the lineman making a mistake in handling.

With regard to the handling of the transformers, some of those now available have lugs, for lifting, cast on the sides of the case and these lugs form a convenient method of pulling the transformers around the floor, so that the leads should not have to be used for this purpose. With some of the modern transformers, the connection to the weatherproof cable leads is made inside of the porcelain outlet bushings, so that it requires considerable mishandling of the leads to injure the transformer insulation, especially with the more substantial high-tension bushings which are now provided.

Considerable attention has also been given, during the past two or three years, to the fuse block question, and porcelain fuse blocks of the receptacle and plug type are now available which are much more reliable and embody most of the characteristics which Mr. Roper sets forth as an index to a good transformer primary cut-out.

I believe that Tables No. IV and V refer to electrical performance of the later types of transformers, while they are

considered in connection with the operating records of transformers of older designs and construction, which would not possess these electrical performances. Changes in the electrical performance may be accompanied by changes in construction that would considerably affect the operating record.

It would seem to be doubtful whether the reduced electrical stress on transformer insulation due to better protection would have any direct effect upon the life of the insulation. Fatigue of the insulation would only come if the stresses were of prolonged duration so that heat stresses would develop, while high-frequency or lightning disturbances are of relatively short duration.

There is no doubt that the better the protection against lightning disturbances, the more reliable will be the operation. There is considerable doubt, however, as to the number of such arresters which it would be practical to install in the average system. Each arrester means an additional link in the system which must be given a certain amount of attention to insure being in good operating condition. Further, the cost for obtaining grounds for each of these arresters would in many cases be higher than that in the city of Chicago, where grounds may probably be obtained at a fairly low cost. Of course, one must have a good ground to have an effective arrester.

It would be desirable to have an accelerated life test as an index of the reliability of the transformer, but it is going to be very difficult to determine on anything in the way of a reliable accelerated life test on a static transformer, such as may be obtained on moving apparatus, as the conditions are vastly different. Practically all that we can do is to study the service conditions, the material that goes into the transformer, see that it is put in in such a way that it will be permanent, that the insulation is properly reinforced, that the temperature rise is low and uniform and look into the various other details of design, construction and methods of manufacture that may affect the relative life of the transformer, but it is very hard to provide any single test as a real measure of such life.

H. W. Hough: As far as we have been able to find out in Cleveland, our experience checks up with Mr. Roper's statement regarding the Chicago conditions. We had approximately ten thousand transformers in service during the past year, and of that number about four hundred were brought in classed as burned out, whether from the coils being burned-out or the leads or terminal boards being damaged. It was a fact that in the great majority of cases the terminal boards were damaged, whether the other effects were there or not. About ten per cent of our transformers have submerged terminal boards, and during the past year there has not been any case on record where the terminal board was damaged when it was submerged. I thought perhaps this statement would add a little to Mr. Roper's side of the question.

Paul M. Lincoln: If we take Mr. Roper's paper at its face value, he apparently has demonstrated that the submergence of the terminal of the connection board is a highly desirable thing in the distributing transformers such as he deals with. I would like to raise the question as to whether Mr. Roper has completely proved that point.

One of the points I want to call attention to is Table No. VI. In Table VI, I think Mr. Roper has shown beyond a question that if a lightning arrester is used in connection with distributing transformers the burn-outs of the transformers are considerably reduced. His own records show that the burn-outs of transformers when a lightning arrester was used on the same pole are about one-third as great as when lightning arresters are not used upon the same pole. Now, a lightning arrester is merely a weak point (usually an air gap) which is used in close proximity to the transformer. I may call attention to the fact that a terminal board which is inside of a transformer serves the same purpose, it is a relatively weak point which lightning can break down. A great disadvantage of making the terminal board or connecting board the weak point is that when lightning does puncture at that point, it blows the fuses, and you have an interruption of service on that transformer, and that is admittedly an objectionable point. I do not believe that this demonstrates that we should not have a connection board above the oil in the transformer, but it should be a connection board having an amount of clearance which makes it, not impossible, but highly improbable, that the lightning will go across inside. That is to say, the design of such a terminal board should be such that it is as strong as the distributing line which is in immediate proximity to the transformer. If you have a terminal board of such a design, that is, so that lightning will go across on the outside of the transformer rather than on the inside, then I think any objection to the terminal boards is removed.

There is one point upon which I want to agree with Mr. Roper, and that is upon the use of fuses for overload protection. Mr. Roper states that the fuse cannot be relied upon an as overload protection, and I believe thoroughly in that point of view. The fuse, when it is used in connection with transformers, is primarily used for the purpose of interrupting short circuits or interrupting something which would cause the service to be interrupted at other points than that one particular transformer, and that is, I believe, its only function. I do not believe that it is possible to design and operate fuses upon our distributing transformers of such a nature as to protect them against overload. I think such a use of a fuse is practically out of the question.

I was very much interested in what Mr. Roper said about the accelerated life test. That is not a new idea, by any means, and if we could find some means of condensing the years into hours, in so far as the life of the transformer is concerned, we would be

very glad to get the results which we should get by such an accelerated life test, but so far, we have not been able to devise any means to accomplish that result, which we believe will be of very great value. If you run the transformer at double temperature for a day or two, that does not give the same result on this transformer as running it at moderate loads for several years; conditions are quite different, and whether the results obtained by overheating very considerably for a short period can be compared properly with the result of the normal life, is a very debatable question. Still, we are not giving up the question, and are still looking for some manner of accelerating the life of the transformer, so that we can crowd the life of the transformer into a few hours, instead of waiting for a good many years to elapse, to get information about the life of the transformer, such as we would have to do otherwise.

Joseph Franz: Representing one of the operating companies, I agree with Mr. Roper in general. Our troubles with the transformers in the Berkshires have been along the same line. Our experience in the matter of placing lightning arresters on the same pole with transformers has shown us that it is not always possible to obtain a good ground connection in isolated or remote sections, and we have had two cases where the lightning arresters failed. The current fused the gaps of a multiple-gap arrester and being connected on the same ground as the secondaries, this condition of the arrester sent the primary current into the building where the service was furnished, and set the building on fire. That caused considerable trouble to our company. Since we had this experience, we place no lightning protectors on the same pole.

Mr. Roper refers to the name-plate, and I would like to add that it would be an advantage to have the manufacturers standardize on the form of the name-plate, its arrangement, as well as having the reading matter in the same order, similar to the way in which the National Electric Light Association has standardized the meter dial faces, so that a man at a glance could read what he wished to read, without going over the whole name-plate.

In regard to the oil, I believe it would be better to adhere to the present practise of having the manufacturers furnish the oil, as it would be very difficult for the smaller companies to select the proper oil for the transformers, and last, but not least, in case of failure the manufacturers could not lay the trouble to improper oil, if it was furnished by them.

M. O. Troy: Actual failures of transformers in service are represented by a very small percentage, yet it is very important that this percentage be reduced in every way possible, as each breakdown may constitute a risk to person or property. Inasmuch as we are dealing with such small percentages, any mere discussion on the part of engineers as to what will or will not decrease this percentage cannot settle the matter, and we have to resort to actual statistics such as Mr. Roper has collected and presented.

In many of our electrical devices, such as the flat iron or incandescent lamp, failure merely means the loss of that device, possibly a little complaint, and replacement if it has not given the service expected of it, but no particular damage is expected or done. The distribution transformer, however, occupies a unique field in that it is supposed to supply these devices uninterruptedly, to take the high-voltage energy, transform it, and to permit the user to apply it to the various current-consuming devices with no misgiving and usually with no question as to safety.

Mr. Roper has pointed out, without resorting to theories or deductions, methods for obtaining greater safety and continuity of service, and has established his contentions by actual results of operation based on observation of hundreds of installations.

Mr. Fishel's plea for standardizationis timely—1100- or 1200-volt plants are rapidly going out of existence, and the time has now practically arrived when, for a large part of this work, we can establish one primary voltage in the neighborhood of 2200 or 2400 volts—possibly as a compromise 2300 volts. This will enable the manufacturers to do away with connection boards, or else to use connection boards merely as lead supports, and with such liberal spacings as will not, under any operating strains, permit failure of the board. If, for convenience in some cases, it is necessary to supply connection boards, my experience, based on observation of hundreds of thousands of units, conforms to Mr. Roper's—namely, that it is better to submerge the boards.

Referring to Mr. Lincoln's contention that in some instances the unsubmerged connection board might be advisable to act as a safety valve by arcing across, blowing the fuses, and disconnecting the transformer—it would seem that this pre-supposes that the transformer strains, from lightning or high frequency, are from one primary to another. Is it not true that the lightning strains are more frequently from primary to ground, and a relief of these strains, via the connection board, assumes that the lightning must, in some way, go from the connection board to the neutral of the secondary? Inasmuch as this method of breakdown is one of the very things we are trying to guard against, it would seem preferable to make the connection board, if it is used, as strong as possible, and to provide a safety valve—say lightning arresters—outside of the transformer.

Another objection to relying on the connection board to discharge high-frequency energy is that the discharge path consists merely of a small number of gaps with no resistance in series, and acts very much like an arcing ground, in that in the very act of relieving the strains, the arc itself may break down the windings.

A great many manufacturers are now carrying two lines of transformers within the voltage range under discussion, namely, 1100/2200 and 1200/2400-volt lines. It would be my recommendation that we supplant these with a line of one primary voltage—say 2300, with a density range in the core, making the

transformers satisfactory for operation under any range of voltage from 2100 to 2400; that we build the transformers as strong as practical consideration of costs, when balanced against results secured, will permit, and provide a safety valve in the way of a well-designed lightning arrester for use outside the transformer. This recommendation, I believe, embodies the standardization idea suggested by Mr. Fishel, and as far as I can see, is in conformity with the recommendations which might be made, based on the statistics submitted in Mr. Roper's paper, and deductions which may be made therefrom.

E. E. F. Creighton: Only those who have been through the experience of collecting a mass of data, and under the various and variable conditions such as exist on a large distribution system, realize how difficult it is, first of all, to gather reliable data, and next, to correlate these data in such a way as to draw any practical and useful conclusions. Breaking a path through any unknown region is always far more difficult than following one already made. The work of months can finally be expressed in a few brief tables and descriptions, giving no comprehension of the labor involved. Mr. Roper's information has been collected at a considerable financial outlay, and has called for careful organization of untrained men. From the standpoint of perfecting electrical protection, the investigation has a great value. It has done more than confirm the results of laboratory experiments. There has been added apparently a new conception of the nature of some surges which were considered harmless.

In the matter of deterioration due to successive strains in the accelerated life tests, it might be pertinent to state that such laboratory tests have been made. Mr. Roper's paper deals particularly with lightning, and in the duplication of lightning it has been possible in the laboratory to furnish any kind of a surge that is required—high frequency, high potential, steep wave front, sloping wave front, etc., and with these discharges, accelerated life tests were made on transformers. In conjunction with this, different types of lightning arresters have been tested out at the same time.

In such tests, applied to many transformers, we have found that there is a deterioration from successive discharges. In nearly every case the transformer is able to withstand more than one discharge. Of course, the number of discharges that the insulation will stand is dependent upon the severity of the discharge, that is to say, in general, upon the voltage and the steepness of the wave front. The tests have shown that successive discharges will deteriorate some types of insulation, in somewhat the same way that a nail is driven through a board by successive strokes of a hammer.

All the laboratory experiments confirm Mr. Roper's statement that there is a deterioration carried on year after year due to lightning.

Very recently Mr. DeBlois gave a paper before the Institute,

at Washington, in which he showed oscillograms of lightning strokes which have different wave fronts, and gave us a very good idea, so far as it goes, of the different kinds of lightning strokes which should be reproduced in the laboratory.

Briefly expressed, some of the salient points brought out by the data so far gathered are as follows: Doing away with exposed terminals reduces the troubles by one-half, placing arresters on the same pole with the transformers has still further reduced the trouble by one-third, and by further improvements in protection the troubles may be again decreased one-half, making a total of one-twelfth the present troubles. Since the total trouble was originally small, a reduction to one-twelfth makes the effects of lightning quite negligible.

The new conception of the danger from surges is furnished by the data which show that where a terminal board is exposed in such a way as to allow a lightning discharge to take place through the case, the transformer is not protected but actually damaged. Short circuits at the terminal of a transformer cut off the coils from the heating effect of the current. What, then, could damage the transformer coils but a surge? Mr. Roper's results show that one-third more transformers were damaged where the terminals were exposed than where they were not exposed. These data have important significance.

Summarizing the situation, all the information collected to date would impose the following practise for the protection against lightning:

First: Have no exposed terminal boards. By that I mean the discontinuance of the practise of using a terminal board as any sort of protection for the transformer.

Second: Place the arrester on the same pole with the transformer. The objection brought up by one of the speakers that different grounds should be used is pertinent, but that has nothing to do with placing the lightning arresters on the same pole with the transformer, as two separate grounds can still be used where desired, and in every case it seems to me desirable to have a gap between the lightning arrester ground, and the ground on the secondary of the transformer.

Third: Use an arrester with good protective qualities. These practical investigations Mr. Roper has made have given us information on the nature of the lightning strokes, that is to say, the percentage of low-frequency strokes to high-frequency strokes, and steepness of the wave front, and therefore we are able today to choose the factors in a lightning arrester to better advantage than ever before.

Fourth: Ground the transformer case to the ground terminal of the arrester, through a gap if desired. Although many engineers differ from this conclusion, my own tests have shown that connecting the case to the ground terminal of the arrester gives a valuable improvement in the protection, in that it makes the protective element of the arrester more nearly independent of the resistance of the earth connection.

There are many places where it is absolutely impossible to get a good earth connection. It has been pointed out that the object in protection is not necessarily to reduce the lightning potential to ground potential, but to prevent a great difference of potential from the primary to the secondary and case. If the lightning arrester is connected from the primary to the case, and through a gap to the secondary, then it is possible to have the transformer, say, at 200,000 volts above ground potential, with only a difference of potential from the primary to the secondary and case of about 6000 or 8000 volts. This point of connecting the lightning arrester to the case is, I believe, the solution of the problem presented by high-resistance earth connections. Furthermore, it eliminates the inductance of 30 ft. of line from the transformer to the ground. It has been demonstrated in practise, by many years of experience, that a short length of line, even the distance from the transformer to the next pole, introduces in the arrester circuit sufficient inductance to greatly decrease the protection of the transformer. Therefore, it is reasonable to conclude that the 30-ft. length from the transformer to ground is also objectionable.

H. B. Alverson: Mr. Roper's paper has pointed out very definitely the troubles occurring with the transformers and the fuses. It is very evident that the transformer ought not to be a lightning arrester, and this one point would argue for a change in the matter of terminal boards in the transformers.

The question of lightning arresters on the same pole with transformers is a very difficult one in city work, where you have joint line construction, and you are compelled to use the same poles with, perhaps, two other telephone companies. The use of a number of lightning arresters on a circuit is bad practise, in case of trouble, when you have to look up the source of trouble. A limited number of lightning arresters properly placed will do as much good, and trouble is easier to locate, than with a greater number of lightning arresters connected with your distributing transformers.

As to the question of fuse box, I believe with Mr. Roper, that that question should be considered entirely separate from that of transformers. The question of the fuse box can be better determined by the nature of the work outside, and the method of locating them on the poles.

W. L. Granger: Nearly two years ago we undertook to standardize our transformer connections, that is, we removed the terminal boards. Of course, the conditions in Detroit are such that it leaves us with a pretty clear course, in other words, there are two entirely independent systems, one operating at 4600 volts and the other one at 2300 volts. We find that we are getting very good results from the change.

In regard to Mr. Lincoln's remarks relative to the proper dimensions of the terminal block at the oil level, it appeared from our experience that the dimensions were of comparatively little

consequence; that is to say, if you had a transformer located in the manufacturing district where there was a lot of smoke and coal soot, the transformer in time is bound to breathe in more or less of this soot and smoke. We found in the summer time that the oil would evaporate and there would be some moisture on top of the block, and this soot and smoke would go right in on it, and it did not seem to make much difference, after a time, what distance you might have between these terminals on the primary side of the transformer. In other words, we found the transformers would break down across the block, due to losses on the lines, in the winter time, even, when there was no lightning, so that we are taking the connection boards out entirely and ordering our new transformers without the blocks at all.

In regard to lightning arresters, I quite agree with Mr. Roper on his proposition of furnishing a lightning arrester for each transformer. It appears, after some observation on my part and some little experience, that this will probably solve the problem.

As to the matter of lightning arresters that break down in service, causing arcing grounds on such a line, last summer I inserted in the line side of the lightning arrester unit a fuse which was a piece of No. 18 copper wire inside a glass tube. It was a very inexpensive affair, placed away from the lightning arrester itself, so that the terminal leading from the fuse into the box is a flexible piece of wire. We have had fairly good success with this device, so that what we are doing this year is to put in these fuses in all of our multi-gap arresters.

W. J. Wooldridge: There are three principal points to which we must look in order to insure reliability of transformers. Two of these points have been touched on, the first being the design, which includes the proper proportioning of insulation and arrangement of cords and connections, etc.; the second being the actual manufacture; and the third being the insulation and protection of installed apparatus.

It is a little out of line, perhaps, with what has been discussed, but I would like to say a word on a certain point, and that is the actual point of manufacture.

It is very essential, of course, that the insulation should be kept intact. The engineer must allow a certain margin of safety when he figures on the amount of insulation to be put in, and part of that margin of safety is to be allowed for possible accidents in the installation; but a great deal depends upon the careful handling of the insulation by the workmen. The workmen, in order to be taught to properly handle the insulation, cannot be successfully reprimanded or coerced, they must be coaxed and trained into understanding the full value of insulation; and in order to put the workmen into a proper frame of mind, the idea of "safety first" has to be thoroughly carried out. The workman must be made to understand that he, too, is being looked after in the same way that he must look after the material.

D. W. Roper: Mr. Moody in opening the discussion brought out the point that co-operation such as is shown in this paper, was desirable. We sometimes have the same difficulty in getting the co-operation of some of our customers—they expect us to relieve them of their troubles without knowing anything about them, and it is only after being properly informed of the troubles which occur that we can take steps to remedy or eliminate them.

On the question of connection boards, on which there was quite a little discussion, the conclusions as reached in the paper were criticised, and it was suggested that an improved design of connection board would have shown quite different results. That is very true, but in the case of an operating company which has no use for a connection board, it does not appeal very strongly to them to experiment in trying to eliminate the difficulties in the connection board, if they can as well eliminate the connection board itself. In Chicago the present practise in purchasing transformers is to remove them before they are placed in service, and in addition, the transformers which come into the storeroom due to changes, such as increase in capacity, or to removals, or changes in location, or other contingencies of that kind, have their connection boards removed before again going out on the line.

The point was raised that Tables IV and V referred to transformers of quite different ages. That is very true. The ages of the various transformers were quite different, and the difficulty was recognized of properly allowing for the difference in age in making up the curves which are shown in these tables. However, if such an allowance had been made it would have served to accentuate the differences shown in the table.

The point was raised of the difficulty of installing lightning arresters on the same pole with transformers on account of the necessity of having a separate ground for the lightning arrester and the transformer secondary. That is a point which comes up frequently, but we have settled it for our purpose by installing the lightning arrester ground on the same pole with the transformer, and installing the secondary ground on a different pole. In most of the installations the transformer secondary serves a number of customers, so we can just as well put the secondary ground on the adjacent pole. Where necessary we string in an additional span of the secondary neutral wire for the purpose of removing the secondary ground to the next pole, and getting it away from the lightning arrester ground.

The question was raised of the additional troubles which would be experienced with the large number of lightning arresters. Our experience with several types of lightning arresters is that, on the whole, the lightning arresters of the present day give comparatively few interruptions to service, and that they are almost as reliable, as far as freedom from interruption of the service is concerned, as the transformers themselves. These remarks do not refer at all to their value as protective devices, but refer to their vulnerablity, as you might call it, or their danger as a source of interruption.

A point was also raised about the grounding of transformer cases. This matter was not mentioned in the paper, not because we have no installations of that kind, but because they have not been in service long enough to have given us any different experiences to report. We have about six hundred transformers whose cases are grounded on three different circuits, and we are trying to keep our records, so we will have some practical experience along that line.

The statement was made that there was some difficulty in getting proper grounds where joint pole line construction was used. A large proportion of the distribution in Chicago is on pole lines jointly owned. The worst that can happen in such a case is that the telephone company may locate a ground for their aerial cable sheath on the pole that you afterwards select as a transformer pole, and the solution of that difficulty is to pay them to remove it to the next pole.

The point was raised that an arrester on each transformer was not necessary. That is true; it is merely a question of the quality of service which the company desires to supply to its customers. With a small number of lightning arresters they can give one grade of service, and with a larger number of arresters they can give a little higher grade. If the smaller number of arresters is sufficient to supply the demand in your particular city there is no object in incurring the additional expense of the larger number of arresters.

Presented at the 296th Meeting of the American Institute of Electrical Engineers, Pittsfield, Mass., May 28, 1914.

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INHERENT VOLTAGE RELATIONS IN Y AND DELTA CONNECTIONS

BY ROYAL W. SORENSEN AND WALTER L. NEWTON

ABSTRACT OF PAPER

The paper gives the results of experiments made with a miniature simple transmission system to demonstrate the inherent voltage relations with different combinations of Y and delta connections.

The experimental system consisted of a 7.5-kv-a. revolving field generator, with coil terminals which could be connected either Y or delta, and two banks of transformers each composed of three shell-type 3-kv-a. units. All inductive and capacity effects in the transmission line were eliminated. The tests were made under constant conditions, with non-inductive load.

The authors give the results of four groups of tests, on four different systems of connections, pointing out the advantages and disadvantages of the several systems. In each case tests were made without load, with balanced load, and with load on one phase only, for various conditions of grounding. Typical voltage diagrams are given, to show what happens under various conditions of load.

The authors discuss certain cases where the use of auto-transformers is advantageous, and the effects of different ways of connecting them.

THE HIGH survival value which the subject of Y and delta systems has as a matter of discussion almost warrants the assumption that inherently neither system can be said to be generally inferior to the other for the transmission and distribution of electric energy. On the other hand, if there is to be any choice of either system, even for special work such as long-distance transmission at high voltage, it would seem as though the choice must be based upon certain features inherent in the method of connections, even though these features may not in themselves be bad, but rather become conducive to trouble only when combined with other features incident to that particular condition.

It is the purpose of this paper, therefore, merely to bring to the attention of those interested, experiments made with simple Y-connected and delta-connected systems and to show, if possible, wherein the advantages of one with respect to the other may lie.

The simplest system which could be constructed would be

that of a single three-phase line supplied at one end through step-up transformers by the generator and at the other end giving out its energy to the connected load through a bank of step-down transformers.

As there can be made with each three-phase bank of transformers four combinations of connections, and as the generator and the receiving motor may be connected either Y or delta, it is readily evident that even in a very simple system there may be made a large number of combinations.

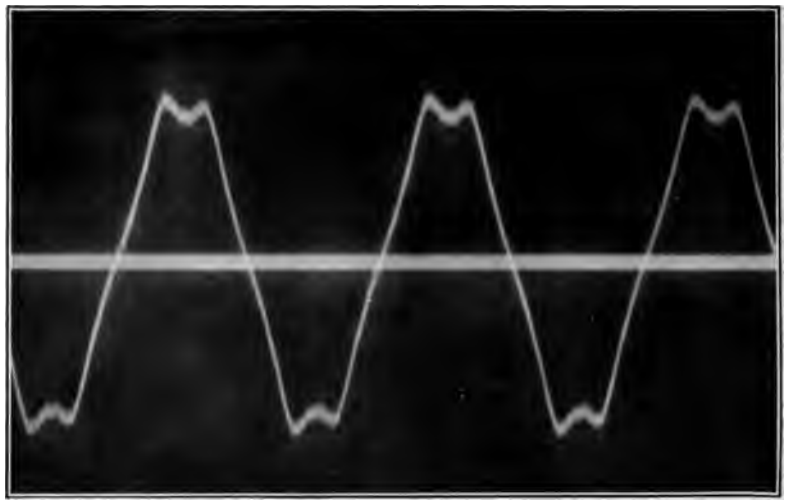
The generators as a rule are connected Y because of the better wave form obtained, as seen in Figs. 1 and 2, and because of the convenient ground point which is then provided. Experience has practically made standard the delta connection for the low-tension windings of both the step-up and step-down transformers, thus leaving for consideration only the arrangements of the high-tension windings of step-up or step-down transformer banks. These may both be connected Y, as has been very generally done, and the neutral points may be grounded or not grounded, the grounded condition being, however, the one in general use. They may both be connected delta or one may be connected delta and the other connected Y, a condition not usual, but one which in some cases has been thought desirable.

Having made a selection as to the arrangement to be adopted in any particular system, it is of course obvious that this system must be carried throughout for any points of multiple connection of transformer banks or transmission lines, because of the impossibility of delta-Y banks being run in parallel with delta-delta banks.

Description of Tests

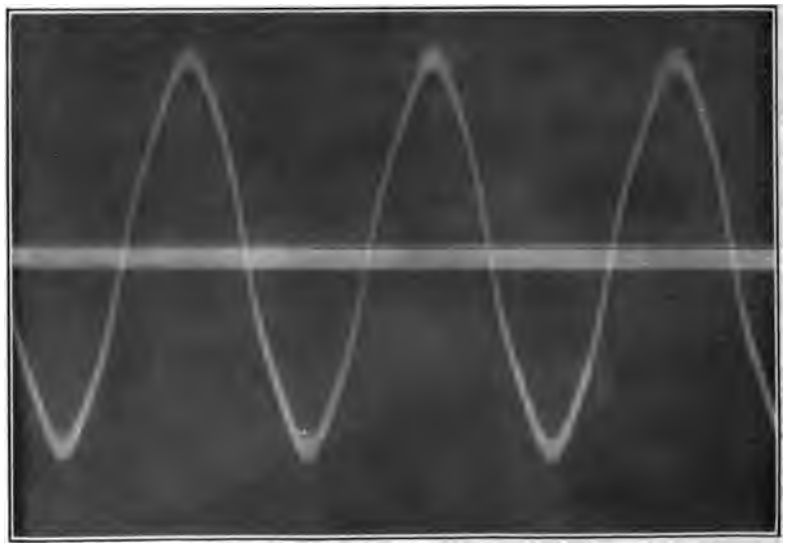
To determine the inherent relations, a miniature system consisting of a 7.5-kv-a. revolving field generator, with coil terminals brought out so that it could be readily connected Y or delta, and two banks of transformers each consisting of three shell-type 3-kv-a. units, was constructed. All inductive and capacity effects in the transmission line, which was in this case only the necessary leads for connecting together the high-tension windings of the step-up and step-down transformer banks, were entirely eliminated. This must be kept in mind when considering the conclusions drawn from the tests.

All tests were made for constant conditions and the load used was non-inductive. Potentials were measured with a multicellular electrostatic voltmeter, which on closed circuits



[SORENSEN AND NEWTON]

FIG. 1—VOLTAGE CURVE, CENTRAL LABORATORY ALTERNATOR. 110 VOLTS, 50 CYCLES. DELTA-CONNECTED.



[SORENSEN AND NEWTON]

FIG. 2—VOLTAGE CURVE, CENTRAL LABORATORY ALTERNATOR. 110 VOLTS, 50 CYCLES. Y-CONNECTED.

was carefully checked with a standard portable dynamometer instrument.

All connections were carefully insulated from each other and from ground, as was also the frame of the generator, except

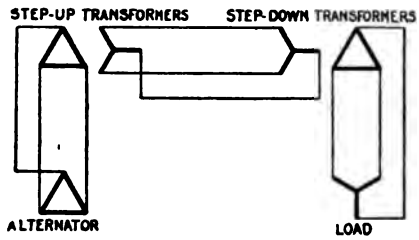


FIG. 3

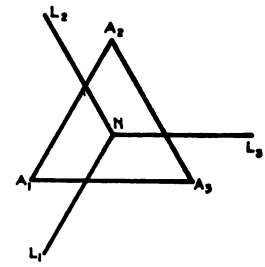


FIG. 4

in such cases as it was well grounded with a copper ground. In all tests the transformer cores and cases were well grounded.

The first group of tests was made on the system connected as in Fig. 3, without load, with balanced load, and with load

TABLE I*

Load	Gr'd point.	Open point.	Maximum per cent volts.				
			H. T. to Gr'd. % H. T.	L. T. to Gr'd. %L. T.	H. T. to L. T. % H. T.	H. T. to L. T. % L. T.	N. to Gr'd % H. T.
0	None	None	57.7	57.7	82.0	163.0	0
0	Neutral	"	"	"	"	"	"
Balanced	None	"	"	"	"	"	"
"	Neutral	"	"	"	"	"	"
1 phase	None	One H.T. line	51.0	69.5	90.0	180.0	18.2
"	Neutral	"	73.0	167.0	138.0	276.0	0
"	None	One load lead	74.5	70.0	100.0	200.0	4
"	Neutral	"	62.4	71.5	104.0	209.0	0
Balanced	One H.T. line	None	100.0	65.0	—	—	—
	N & 1 " "	"	91.2	57.7	—	—	0

*In these tables readings with ungrounded generator frame are omitted (exceptions noted in Tables II and IV), as this condition so rarely exists in practise.

on one phase only, for various conditions of grounding. Some typical results of these tests are shown in Table I. When one phase only is loaded, such condition is obtained in one of two ways: by opening a high-tension line, or by opening a low-tension line on the load end.

Fig. 4 shows the no-load voltage diagrams of high- and low-tension lines superimposed upon one another. The step-up and step-down transformers being identical, the delta represents voltages of generator, primaries of step-up transformers and secondaries of step-down transformers. Line voltages, secondaries of the step-up, and primaries of the step-down transformers are shown by the Y. If, as was assumed, the diagram is drawn to scale, it would be supposed that a measurement from any point on the delta to any other point on the Y would give the voltage between corresponding points on primary and secondary of transformers. This, however, was found not to be true in many instances. With no ground point on the system except the transformer cases, the electrostatic strains would be anywhere from 50 to 100 per cent greater than the values obtained by measurements from the diagram. The neutral point of the Y, which should normally be at ground potential, was found to be at some distance above. It was in fact found

FIG. 5 FIG. 6

that no point on the entire system was exactly at ground potential, except of course the transformer cases, and even the frame of the alternator was found to be at a potential above ground greater than normal line voltage. These facts can lead to but one conclusion, namely, that the conditions on all systems cannot be truly represented on one plane.

On this assumption, a great number of readings were taken, and it was found that each section of the system might lie in a totally different plane, but that these planes are always approximately parallel.

An end view, then, of Fig. 4 would appear as in Fig. 5, in which each line represents the plane on which the respective diagrams would have to be drawn to represent correctly the readings obtained. No definite law seems to govern the relative position of these planes. On one day the distance between them may be twice that obtained on another. However, the primary and secondary planes are always on opposite sides of ground, as shown.

The grounding of the Y neutral brings the transmission line plane to ground potential, but maintains a nearly constant potential between this plane and the generator plane, so that the potential between generator plane and ground is doubled, as in Fig. 6. When the generator frame, which heretofore had been well insulated, was thoroughly grounded, all potentials were brought to the same plane and the voltages read corresponded to those measured from the diagram, in Fig. 4.

As load is added to the ungrounded system, the distance between the respective planes decreases, and appears to be some function of the load. When loaded, the difference between them is inappreciable. This is true of unbalanced as well as balanced loads. Conditions, then, are better at load than at no load, or very light load. (See Table I.)

The second group of tests was made with the same trans-

TABLE II

Load	Gr'd point.	Open point.	Maximum per cent volts.				
			H. T. to Gr'd. % H. T.	L. T. to Gr'd. %L. T.	H. T. to L. T. % H. T.	H. T. to L. T. % L. T.	N. to Gr'd % H. T.
† 0 Balanced	None "	None "	57.7 "	61.0 "	85 "	167.0 "	0 "

†Generator frame not grounded.

former arrangement but with the generator connected Y. The tests made under these conditions gave results as in Table II, which are very similar to those of the first group, in that there still remains the tendency for the voltage planes to separate on the ungrounded system, at light load. This condition is probably better, however, than the first, due to the better wave shape obtained with the generator in Y, as can be seen by a comparison of Figs. 1 and 2.

From these data the following conclusions for a Y-connected transmission line may be drawn: The generator should be connected Y. The neutral point should be well grounded at both ends to relieve electrostatic strains. There is, of course, the objection to a grounded neutral, that if a line becomes grounded also, one phase is short-circuited. The second point, which fortunately does not often arise in practise, is that all alternator frames, motor frames, and transformer cases should

be thoroughly grounded, not only for the foregoing considerations, but also to protect the lives of operators and linemen.

The disadvantages of Y-connected transmission lines may be summed up: Difficulty of obtaining a satisfactory ground on the neutral, and overload or short circuit of one phase by partial or complete grounding of a line.

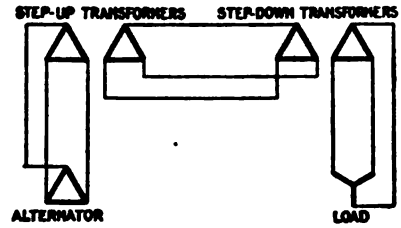


FIG. 7

The third group of tests was made with the system connected as in Fig. 7, with the same load conditions as in the previous set of tests. With this arrangement the normal stresses are about the same as with the Y connections (see Table III), and the unbalancing of load causes no serious variation in voltage relations, but there remains the tendency for the circuits to

TABLE III

Load	Gr'd point.	Open point.	Maximum per cent volts.				
			H. T. to Gr'd.	L. T. to Gr'd.	H. T. to L. T.		N. to Gr'd
			% H. T.	%L. T.	% H. T.	% L. T.	% H. T.
0	None	None	58.3	57.7	91.2	105.0	—
Balanced	"	"	"	59.0	"	"	—
1 Phase	"	OneH.T. line	60.1	69.1	104.0	120.0	—
"	"	One load lead	65.0	67.2	109.0	126.0	—
0	OneH.T. line	None	100.0	64.5	135.0	156.0	—

lie in different planes, which separate decidedly with a removal of the ground connections to the generator frame. In this case, again, the bad wave form of the alternator connected delta is objectionable. On the whole this system is not to be recommended, as conditions seem to be particularly unstable, and there is no possibility of obtaining a ground point if occasion demands.

The fourth group of tests was made with the same transformer connections as in group three, but with the generator connected Y, giving the better wave form. This is apparently the ideal condition, as with such an arrangement it is unnecessary to ground this neutral in order to relieve abnormal elec-

TABLE IV

Load	Gr'd point.	Open point.	Maximum per cent volts.				
			H. T. to Gr'd. % H. T.	L. T. to Gr'd. %L. T.	H. T. to L. T. % H. T.	H. T. to L. T. % L. T.	N. to Gr'd % H. T.
† 0	Gen. N. (Ng)	None	58.7	57.7	94.4	109.0	0
"	None	"	58.2	"	"	"	3
Balanced	Gen. N.	"	57.7	60.0	"	"	0
1 Phase	"	OneH.T. line	71.7	90.0	167.0	192.0	4
"	"	One load lead	81.2	84.0	142.0	164.0	"
0	1 H. T. line & Ng	None	100.0	58.0	145.0	167.0	"
"	OneH.T. line	"	"	63.7	148.0	168.0	"
Balanced	1 H. T. line & Ng	"	"	58.0	145.0	167.0	"

†Generator frame not grounded.

trostatic strains between windings. (See Table IV.) All neutral points remain close to ground potential, even under unbalanced load. There being no grounded neutral on the system, the danger of a short-circuited phase by grounding is entirely obviated, unless two lines should become grounded simultaneously.

Voltage Diagrams

A few voltage diagrams might help to make clear just what happens under various conditions of load. To avoid needless repetition of similar figures, diagrams of the results obtained in the fourth group of tests are taken as typical.

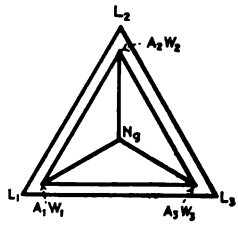


Fig. 8

Fig. 8 represents conditions under balanced load, in which the Y is the generator diagram, with the neutral at *Ng*. The delta A_1, A_2, A_3 represents the primaries of the step-up bank of transformers, and L_1, L_2, L_3 the secondaries of this bank and the primaries of the step-down transformers. The diagram of the secondaries of step-down

transformers connected in Y, corresponds to A_1, A_2, A_3 and is indicated by W_1, W_2, W_3.

If, now, one line is opened between step-up and step-down transformers, conditions result as in Fig. 9, which is lettered to correspond with Fig. 8. The heretofore symmetrical figures become considerably distorted. W_1, W_2, W_3 becomes a straight

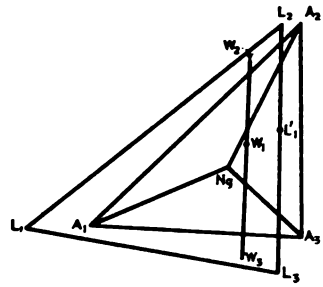


FIG. 9

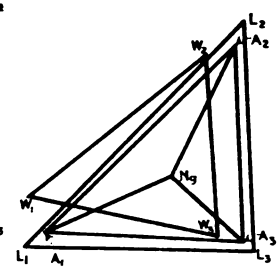


FIG. 10

line, and is therefore in series from W_2 to W_3. The diagrams of the secondaries of the step-up bank and of the primaries of the step-down bank of transformers are no longer coincident. The former is shown by the triangle L_1, L_2, L_3 and the latter by the straight line L_2, L_1', L_3. The distance L_1-L_1' represents the voltage across the open switch.

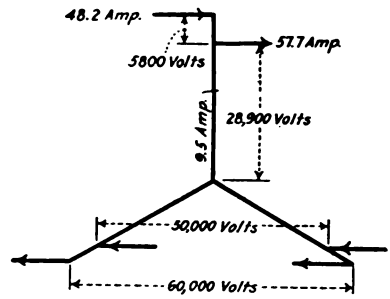


FIG. 11

An open line between step-down transformers and the load gives Fig. 10. The distortion is not so noticeable as in the previous case.

AUTO-TRANSFORMERS

The economic advantage of using auto-transformers for changing from one phase to another and for making slight

voltage changes when it has not been necessary to keep the two systems insulated from each other, has caused them to be quite extensively used.

Example: A certain large power company had as one source of supply a plant which delivered power to the main distribution center, over a 125-mile (201-km.) line, at a potential of 50,000 volts. In the new development 60,000 volts was selected

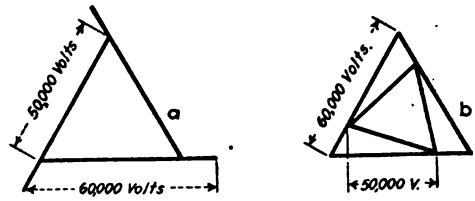


FIG. 12

as a standard for long distribution feeders, and as the line insulation would not permit the old system to be raised to this voltage, the two projects were tied together by means of three auto-transformers, which were Y-connected and would carry, on the 50,000-volt taps, 5000 kv-a. The connections and currents for this bank of auto-transformers are shown in Fig. 11.

This is the most common arrangement of auto-transformers because it is both convenient and economic, and the only one

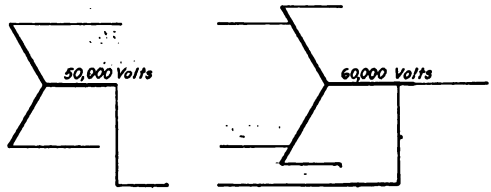


FIG. 13

which will be considered, although either the extended delta or the delta connection as shown in Fig. 12, *a* and *b*, might have been used to good advantage.

When such an auto-transformer is used, it is connected as in Fig. 13. For such an arrangement there may be two conditions; grounded neutral and ungrounded neutral. With grounded neutral the triple-frequency e.m.f. which exists from line to ground may become very dangerous, particularly if the line has

considerable electrostatic capacity, as would be the case in the assumed problem, because of the intensifying effect of the third harmonic in the charging current. In some tests made, the maximum stress was found to approach three times normal potential for the neutral of the auto-transformer bank grounded.

With the neutral of the auto-transformer bank ungrounded, stresses running up to 50 per cent of line voltage may be measured from ground to neutral, which is of course not a serious matter, as the maximum stress will remain from line to ground and will not be changed from normal value.

Laboratory tests for this connection indicated that the maximum voltage strain from the lower potential lines to ground would be about half the sum of the high-voltage and the low-voltage, which in this case would be one-half of 60,000 volts plus 50,000 volts, or 55,000 volts.

Transformer Design

When transformers were made in small sizes only, particularly if they were shell type, there was some advantage in having the windings connected Y for the high-tension side of the bank, as this allowed a smaller number of coils and less insulation, because the normal strain was 57.7 per cent of that of delta-connected transformers. The increase in size of units and the provision for maximum strain where one line becomes grounded have made these economic advantages obsolescent, except in some very special cases of small, high-voltage units. Hence, from the point of design and manufacture, there is no advantage for either Y or delta construction.

Appendix

It may be of interest to consider an actual network diagram of the system of a large western power company, as shown in Fig. 14. The following nomenclature is used:

A, engine-driven alternator.
TA, turbine-driven alternator.
T, transformers.
AT, auto-transformers.

The numerals indicate the voltage at various points on the system. For simplicity, the location of switches has not been shown. Several small generating stations on the system are not shown.

Power house No. 1 contains three (shown as one in diagram) engine-driven alternators delivering power at 15,000 volts directly to the busbars. The two turbo-generator sets generate at 9000 volts and step up to the busbar voltage through auto-transformers. In substation No. 1 this is stepped up through transformers to connect with a 50,000-volt line, and in substation No. 2 it connects with a 60,000-volt line through transformers.

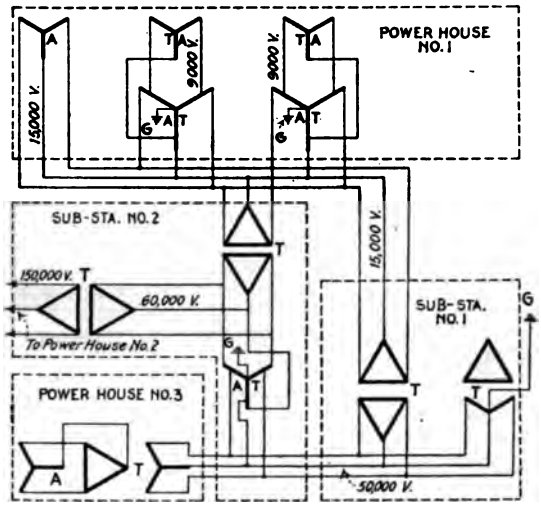


FIG. 14

Power house No. 2 (not shown) is a hydroelectric plant. The generator voltage is stepped up with delta-Y (grounded neutral) transformers to 150,000 volts, at which voltage it is delivered to substation No. 2, where it is transformed to 60,000 volts as shown. The 50,000-volt line from power house No. 3 is connected to the 60,000-volt line through auto-transformers. Substation No. 1 contains a bank of transformers connected Y-delta, with the neutral grounded and the secondary on open circuit.

Presented at the 296th Meeting of the American Institute of Electrical Engineers, Pittsfield, Mass., May 28, 1914.

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HARMONIC VOLTAGES AND CURRENTS IN Y- AND DELTA-CONNECTED TRANSFORMERS

BY R. C. CLINKER

ABSTRACT OF PAPER

The paper reviews the conditions under which triple harmonic voltages and currents are produced in Y-and delta-connected transformers. These voltages are produced by hysteresis in the core. In a single-phase transformer, increase of series resistance tends to suppress the current harmonic and produce the voltage harmonic. In three-phase transformers, a Y connection suppresses the current harmonic and allows the full flux and voltage harmonics to appear. Delta connection provides a closed path for the current harmonic, and suppresses the triple voltage.

A case is cited where a Y-connected auto-transformer was used to step up from 6600 to 12,000 volts at a substation. The neutral was not grounded, and trouble resulted due to partial resonance at triple frequency between line capacity and transformer reactance. The paper shows that, although not generally recognized, a triple component can exist in the line-to-line e.m.f. wave of a three-phase system. This is possible in a case where a two-to-three-phase transformation is used, and when the e.m.f. wave of the two-phase generator contains a triple harmonic. Vector diagrams and curves are given illustrating this possible effect.

IN CONSIDERING the relative advantages and disadvantages of Y and delta connections of transformer windings, it is necessary to pay some attention to the production of harmonic voltages and currents occurring in such windings due to hysteresis in the core. This has been treated by several since the present writer first drew attention to the effect,[1] but it may not be out of place in the present discussion to review briefly the conditions under which such harmonics become noticeable, and to point out a further possible case which, so far as the writer is aware, has escaped notice.

If we take the case of a transformer winding connected to an a-c. source of supply, we find that though the e.m.f. wave may be sine-shaped, the current wave necessary to produce the sine flux wave contains harmonics, notably a third and a fifth, which are produced by hysteresis and by the variation of permeability of the iron. These current harmonics may be regarded as in-

1. See the *Electrician* for 10th November 1905 and 5th January 1906.

duced in the circuit by harmonic flux variations arising in the core. In such a case, however, the current harmonics produced "wipe out" almost completely the flux harmonic, because the resistance of the circuit is usually low. Hence the value of flux harmonic actually existing is only that sufficient to induce a voltage in the coil equal to $i \times r$, where i is the harmonic current, and r the resistance of the winding. By increasing the resistance, however, the flux and voltage harmonics become very noticeable, and a distorted wave form appears across the coil terminals. (Incidentally, this has an important bearing upon the use of series resistance for varying the voltage of an insulation-testing transformer, which sometimes results in the production of a high peak voltage. One remedy is to shunt a resistance across the transformer terminals, which allows of the use of a lower series resistance and therefore, reduced distortion). Without increasing the resistance, however, there is another way by which the current harmonic may be suppressed, viz., by the use of a star-connection of circuits, using the term "star" in its general senses implying n circuits for an n-phase system. A little consideration shows that the nth harmonic of e.m.f. induced by the iron is directed in each circuit simultaneously towards or away from the neutral point, and that therefore no current of this frequency can flow. Hence, with a three-phase Y connection, the triple component of the magnetizing current is eliminated, and the full triple-frequency flux variation occurs, producing a distorted wave form of high peak value, across each winding. With a Y-Y connection of transformers, particularly with single-phase transformers or shell type three-phase transformers, the full flux variation occurs. In the case of one set of windings, either primary or secondary, being delta connected, the flux variation is almost wholly suppressed by the circulation of the triple-frequency current in the closed triangle. From this point of view, therefore, a delta connection on either primary or secondary is desirable, as (1) It avoids the extra insulation stress due to the higher peak voltage, and (2) In the case of a transmission line with grounded neutral, it prevents triple-frequency capacity current in the ground wire, which, in the case of long transmission and high voltage, may reach a high value. In core-type three-phase transformers, the triple-frequency voltage is not marked, as the magnetic circuit of the flux harmonic is a partly open one, the path being up the three limbs in parallel and back through the air or tank. Oscillograms showing the

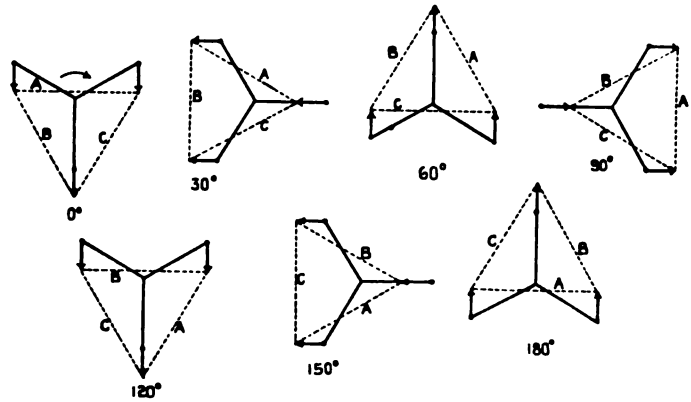
conditions obtained in various cases were presented in an interesting paper by Mr. J. J. Frank, before the A. I. E. E. in May 1910. A case where trouble occurred which could only be ascribed to the above effects was brought to the writer's notice some time ago. The conditions were as follows:

From the power house, a five-mile 6600-volt line ran to a substation, where the voltage was raised to 12,000 by two Y-connected auto-transformers of 600 kv-a. capacity, with insulated neutrals. The 12,000-volt line supplied a substation five miles away, where step-down transformers were installed. Trouble was experienced due to the gap arresters on the 12,000-volt line continually sparking to ground. Also two breakdowns on terminal leads occurred, and there were other general indications of high voltage to ground, although the line to line voltage was correct. Voltage readings between the three lines and the auto-transformer neutral, on the 12,000-volt side, showed that with normal phase voltage on the transformer and the 12,000-volt line disconnected, the pressure between each 12,000-volt terminal and neutral was 17 per cent greater than the phase voltage $\div \sqrt{3}$. When the 12,000-volt line was switched on, the voltage to earth rose further to 33 per cent above the normal value. Grounding the neutral of the auto-transformers cured the trouble, and reduced the voltage between the 12,000-volt lines and the ground to normal. It should be noted that the neutral of the generators was grounded through a low resistance at the power house. A ready explanation of these effects is afforded when the triple-voltage harmonics induced in the transformers are taken into account. With 12,000-volt lines disconnected, there is a 17 per cent increase of voltage to ground due to triple harmonic. This is aggravated, however, when the 12,000-volt line is connected, due to partial resonance, the capacity being in series with the high reactance of the auto-transformer winding. In this case the circuit is completed through the grounded generator neutral and the 6600-volt line. The effect of grounding is to connect the neutrals of generator and auto-transformer, and allow the triple component of current to be supplied, thus eliminating the voltage harmonic.

It has sometimes been stated[2] that no triple harmonic can exist in the e.m.f. between the lines of a three-phase system. It appears to the writer, however, that, though not often met with

2. See Steinmetz, paper before N. E. L. A., June 1907, also Rhodes, TRANS. A.I.E.E., 1910.

in practise, such an effect is quite possible. Consider the case of a two-phase generator supplying a three-phase line through Scott-connected transformers, and suppose that the generator



FIGS. 1-7—DIAGRAMS SHOWING TRIPLE HARMONIC IN THREE-PHASE SYSTEM AS PRODUCED BY THREE-PHASE GENERATOR OR BY Y-CONNECTED TRANSFORMERS—DOTTED TRIANGLE SHOWS LINE-TO-LINE E. M. FS.

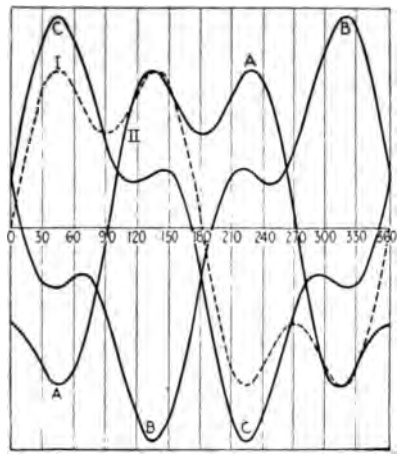


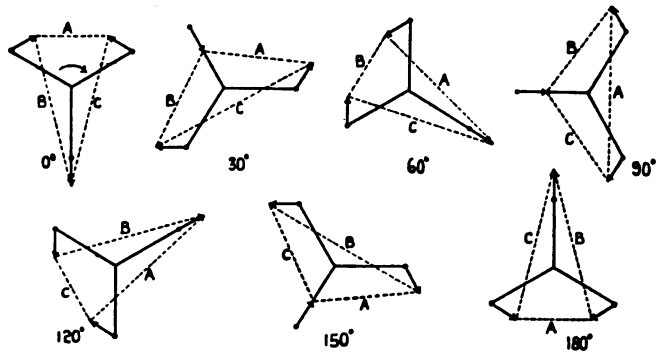
FIG. 8—WAVE SHAPES OF E. M. FS. BETWEEN LINES OF THREE-PHASE SYSTEM, SHOWING TRIPLE HARMONIC TRANSFORMED FROM TWO-PHASE SYSTEM.

Curves I and II two-phase e.m.fs. Curves A, B and C three-phase e.m.fs. See Figs. 9-15 for vector diagrams.

e.m.f. waves contain triple harmonics. As the main waves differ by 90 deg. in phase, the harmonics in the two phases will differ 3 × 90 deg. or 270 deg. in phase, *i.e.*, they will be in quadrature. Hence we have a two-phase supply at triple frequency

impressed upon the primary, and this is transformed to a three-phase e.m.f. at triple frequency, which appears between the lines as a superposed harmonic on the fundamental three-phase e.m.f. It is a curious fact that this effect cannot be obtained by direct three-phase generation, but, apparently, only by transformation from a two-phase supply. The accompanying diagrams will make clear the difference between the two cases, viz., (1) Triple harmonic due to three-phase generator, or Y connection of transformers. Harmonic appears only between line and neutral, and not between lines. Figs. 1 to 7 show the vectors at progressively varying phases, during one-third of a cycle.

(2) Triple harmonic impressed on system by two- to three-phase transformation. Harmonic appears both between lines,



FIGS. 9–15—VECTOR DIAGRAMS SHOWING TRIPLE HARMONIC TRANSFORMED INTO THREE-PHASE SYSTEM FROM TWO-PHASE SYSTEM. (SEE FIG. 8 FOR WAVE SHAPES.)

and between each line and neutral. Fig. 8 shows the three-phase waves produced between lines, assuming particular values for the amplitude and phase of the triple harmonic in the two-phase e.m.f. Curves I and II are the assumed two-phase waves, having exaggerated harmonics. A, B, and C are the resulting three-phase line voltages. Note that these waves are dissimilar.

Figs. 9 to 15 give the vector diagrams corresponding to Fig. 8. The dotted line A, representing one of the three-phase line voltages, also represents by its projections on vertical and horizontal the two-phase voltages I and II respectively.

The writer is not aware of any previous reference to this possible effect, and it would be interesting to hear if such has been observed on any line employing two- to three-phase transformation.

DISCUSSION ON "INHERENT VOLTAGE RELATIONS IN Y AND DELTA CONNECTIONS" (SORENSEN AND NEWTON) AND "HARMONIC VOLTAGES AND CURRENTS IN Y- AND DELTA-CONNECTED TRANSFORMERS," (CLINKER), PITTSFIELD, MASS., MAY 28, 1914.

Waldo V. Lyon (by letter): The interesting fact that Mr. Clinker notes in regard to the possibility of a third-harmonic voltage existing between the lines of a three-phase circuit was observed by the writer some time since, and was used as the basis of one of the problems in a collection* recently published by him. These third-harmonic components in the line voltages are equal but differ in phase by 120 degrees (third-harmonic scale) so that the circuit should respond to their influence in the same way that it would if sinusoidal voltages of three times the fundamental frequency were impressed upon it. This might produce serious results, especially in transmission lines, if the harmonics were of sufficient magnitude. This phase difference in the third harmonic makes the resulting three-phase voltages, dissimilar as Mr. Clinker points out. Their effective values, however, are equal.

In a three-phase generator the voltage, reduction factor for the third harmonic, assuming a phase spread of one-third and a coil pitch of one, is about 64 per cent. On the other hand, in a two-phase generator this reduction factor, assuming a phase spread of one-half and a coil pitch of one, is about 30 per cent. The corresponding reduction factors for the fundamental in the two-phase and three-phase generators are 96 per cent and 90 per cent. These factors are for a winding that is completely distributed. Thus, for the same flux distribution and the same phase voltage, the third harmonic component would only be $\frac{30 \times 96}{90 \times 64}$, or one-half as great in a two-phase generator as in a three-phase generator.

A. E. Kennelly and Harold Pender (by letter): In connection with Mr. Clinker's observation on a rise of pressure of 37 or 33 per cent in different cases, attributable to partial resonance, with triple harmonic frequency, we may mention that on an artificial line at the Massachusetts Institute of Technology, built to represent a three-phase aerial three-wire 500,000-circular-mil conductor system 240 miles long, a voltage rise of 20:1 was observed experimentally by us at a frequency af 189~ which is substantially a triple harmonic frequency to the standard frequency of 60 ~. That is, when this length of artificial line was operated with 50 volts at the generating end and with 189~, the voltage at the distant free end reached 1000 volts, and this result checks very well with the theoretically deduced value.

*"Problems in Alternating Current Machinery," Problem 10, p. 127.

The application of the above-mentioned result to voltage regulation on a fairly long transmission line will be evident in the case of a voltage containing a high harmonic to which the line may happen to be a quarter wave length. For example, a line 240 miles long would be roughly quarter wave length to a third harmonic in a 60-cycle generator voltage wave. A five per cent harmonic at the generator would produce a 20 × 5 equals 100 per cent third harmonic at the receiving end at no load and so might produce, in combination with the fundamental, a peak voltage of twice the peak voltage at the generator.

F. W. Peek, Jr.: I was much interested, in reading these papers, to see the number of times the "third harmonic" was referred to or discussed. There are a great many phenomena existing in engineering which are not generally observed until something happens to make them annoying in practical work.

In certain transformer connections the third harmonic, inherently in the magnetizing current with applied sine wave voltage, is the cause of abnormal stress to ground. This is especially so with long lines of high capacity.

If Y-connected auto-transformers, with their neutral grounded as the only ground, are used to step up the generator voltage, *abnormal potentials to ground* may result. These excess voltages are *not indicated by a voltmeter, but by "static" on leads*, excessive losses, or *by a spark gap* connected between one line and ground. The reason that a voltmeter does not indicate this high voltage is that the effective value of the voltage is not greatly changed, but only the maximum value of the wave is increased, and this is indicated by a spark gap, or stress between the insulation and ground. The cause of the voltage distortion is as follows:

When a sine wave e.m.f. is applied to a transformer, the resulting magnetizing current wave cannot be a sine wave but must follow the changing permeability of the iron,—this current wave contains the third harmonic. The current and voltage waves can never be the same, but, if the magnetizing current wave is a sine wave, the voltage wave must then contain a third harmonic, or *vice versa*. Hence, if anything prevents or suppresses the third harmonic in the magnetizing current the applied sine wave of voltage must then become distorted.

In a three-phase transformer the currents are 120 deg. apart for the fundamental frequency, or 3 × 120 or 360 deg. apart for the third harmonic; that is, in phase. Thus for Y-connected auto-transformers the triple-frequency magnetizing currents to neutral must be in phase. The sum of the three currents flowing to a point must be zero. Hence, as the third harmonic magnetizing currents are all in phase, they must all be zero to satisfy these conditions; that is, they must be suppressed. This means that the current wave approaches a sine and that therefore the voltage to neutral cannot be a sine wave but must be peaked, or contain the third harmonic, which appears as voltage rise to neutral and causes extra iron and insulation loss. The distortion does not appear in the voltage between lines because

the distortion between one line and neutral is cancelled by that of the other two lines. The voltage distortion may be eliminated by supplying a path for the triple-frequency exciting current; that is, in this case, by connecting the transformer neutral to the generator neutral. This supplies a single-phase circuit for the triple frequency through the line and generator. A current of the proper phase relation flows and the distortion disappears.

If, before this connection is made to the generator, the transformer is connected to a transmission line, a path is supplied for triple-frequency current through the capacity from line to ground. This capacity offers three single-phase circuits. A triple-frequency current thus flows but it has not the proper phase relation for the triple-frequency excitation current, and instead of eliminating the voltage distortion it greatly increases it. A double peak may occur in the fundamental voltage wave which causes an increased iron loss. This distortion, however, also generally disappears when the auto-transformer neutral is connected to the generator neutral. Without this inter-connection the distortion is greater in the case where the transformer is connected to a capacity. The peak of the wave may be several times normal. The effect of capacity is well brought out by Mr. Blume. There are other ways of supplying this third-harmonic current; for instance, by a closed delta in the transformer.

If a grounded-Y auto-transformer is used to step up the voltage of a generator with non-grounded neutral, and at the far end of the line is a transformer with grounded Y on the line side and delta on the low side, triple-frequency current is supplied from this transformer to the auto-transformer through the ground by the three single-phase paths. These ground currents may cause telephone troubles; if the transformer at the far end is small compared to the auto-transformer, the triple-frequency exciting current may overload it and cause it to burn out.

The third harmonic is thus a " constant current " effect, that is, the voltage drops when triple-frequency current with the *proper phase relation flows* through a low-resistance path. If the circuit has high resistance the voltage becomes high.

There may also be a third harmonic in the generator wave, due to the relation of the windings, which has a " constant voltage " effect and which may produce very *heavy triple-frequency currents* with improper connection, or when a short circuit path is afforded for these currents. Precautions are thus necessary where several generators are connected in parallel and the neutrals grounded. If all of the generators are of identical design, very large triple-frequency excitation currents may flow unless the field excitation is the same on all of the generators. If the generators are not of identical design, dangerously large triple-frequency currents may result. When a number of generators are operated in parallel and the voltage is stepped up by auto-transformers, it is often practicable to ground only one generator

at a time and to connect to this ground all of the transformer neutrals.

Whenever auto-transformers are used it is necessary to investigate the possibilities of trouble for the particular case under consideration. Their use is generally not to be recommended.

There are other transformer connections which may cause high triple-frequency voltages, as an instance, Y-Y.

Louis F. Blume: In connection with Mr. Clinker's paper, I wish to point out that the Scott-connected transformer should not be held responsible for the third harmonic which appears in the three-phase system. If the Scott-connected transformer had been omitted, and the generator connected in "T", the third harmonic would have appeared in the line just as described.

F. C. Green: Reference is made in the paper by Messrs. Sorensen and Newton to some experiences that were had in a western system. I happened to be connected with the installation of that system, and made some tests on triple-frequency effects related by the authors in their paper.

For the tests, the bank of compensators was excited at 60,000 volts and stepped this voltage down to 50,000 volts. The neutral was not grounded except for the slight grounding effect that resulted when measuring potential between neutral and ground by means of a potential transformer. Tests were made with the auto-transformers open on the 50,000-volt side and also with them feeding into the 50,000-volt system, there being practically no difference in the measured values for the different conditions. With 60,000 volts impressed, the voltage between neutral and 60,000-volt terminals was 42,000 volts; between neutral and ground, 18,600 volts; between 60,000-volt terminals and ground 36,600 volts. All measurements were made with potential transformer. No tests were made under the condition that had caused trouble, namely, with only the auto-transformer neutral grounded in the 50,000-volt system; the reason being fear of damage to the line.

Under the system of connections that was planned to be used there, the grounding of the neutral would not have caused any excessive voltages. On occasions of line disturbances, it sometimes happened that all other grounded neutrals in the system were disconnected, leaving only the auto-transformers' neutrals grounded.

Mr. Clinker mentions in his paper an instance where trouble due to triple-frequency effect was relieved by grounding the auto-transformer neutral. In the system discussed above, it was necessary to unground the neutral to prevent damage. The theory for this case is given in Mr. Blume's paper.

Triple-frequency effects have been well covered and there is now no reason for experiencing any more trouble from them. Until some new phenomena develop in operation, due to their existence, it seems that efforts should be directed to the solution of other and more vital features of the subject under discussion.

C. L. Fortescue: In connection with Mr. Clinker's paper, if I am not mistaken, in previous discussions on a paper by Mr. Frank this peculiarity of the Scott connection has been pointed out. The third harmonics which exist in the two-phase generator are transformed, so that they appear in the three-phase circuit in three-phase relation after transformation. This will be found to be true also in any transformation or any generation, whether produced in a generator or transformed in a transformer in which there is dissymmetry in the phases. The triple harmonic effects present will appear in three-phase relation, causing differences in the wave forms of the voltages between the mains as a result of dissymmetry in the windings of the transformers or in phases of the generator.

P. M. Lincoln: This observation brought out in Mr. Clinker's paper is of interest to me, because in studying the wave forms of the Niagara Falls generator, which was installed about nineteen years ago, I observed the same thing. The Niagara generators had slightly flat-topped waves, similar to those Mr. Clinker has shown. If you take a two-phase generator, such as we had at Niagara, and get three phases from it by the Scott connection, you will have one of the phases going through the transformation with the wave form unchanged, the same on the three-phase as on the two-phase side. That will be what we may call the main phase. Of the other two, one of them will be a peaked wave and the deformation will be to one side of the neutral axis, say on the right-hand side. You will find the other phase will be exactly similar, except that the peak will be formed on the left-hand side. If you start with a peak wave, you will find when you get through to the three-phase side, you will have one peak wave and two flat-top waves, distorted, one to the right and the other to the left. It is not a new observation, by any means, and has been known for a great many years.

J. M. Weed: I wish only to raise a point of theoretical interest in connection with Mr. Clinker's paper. Mr. Clinker has attributed the third-harmonic component in exciting currents to the effect of hysteresis. To see that this is not correct, it is only necessary to consider that hysteresis constitutes an energy loss in the iron, and that with a sinusoidal voltage applied, energy can be supplied only by current of the same frequency as the voltage, *i.e.*, by a fundamental component of the exciting current. The triple harmonic and all higher harmonic components of the exciting current are not due to hysteresis, but to the permeability characteristics of the iron; *i.e.*, to variations in permeability with changes in the magnetic density.

D. C. Jackson: As Dr. Kennelly referred to the artificial line at the Massachusetts Institute of Technology, it will be interesting to add that it is a line made up of No. 12 B. & S. gage wire that has resistance, self-inductance and capacity which causes it to represent substantially 750 miles of length of line, 500,000-circular-mil conductor, spaced at 8 feet, center to center.

That is about the line which would be used for the transmission of power from the Falls of the Nile to South Africa.

The one-third length which Dr. Kennelly used in his experiments was a part of that line. The reason for the line being built of the No. 12 B. & S. gage wire was to make it practicable to use ordinary portable ampere-meters, voltmeters, or wattmeters in connection with it, without interfering seriously with its normal performance. As far as tests have gone, that seems to be what can be done, and makes it very convenient. One can find out the operating characteristics of the line by using portable ampere-meters, voltmeters or wattmeters, in the ordinary fashion, apparently, and do it in relatively little time. I think, in the case of the Schenectady line, it is necessary to have special instruments to be used with the experimental line, it being of small wire of relatively high resistance.

This line at the Massachusetts Institute of Technology when operated at 60 cycles, open circuit, pure sine wave, gives a rise of voltage of about 9 to 1 in the full length, that is, 120 volts impressed at the generator end gives something over 1000 volts at the receiver end, open circuit. Of course, a very small load on the line changes that promptly, as the formula shows.

The line responds closely to what the formula indicates, although it is what is called a lumpy line.

Presented at the 296th Meeting of the American Institute of Electrical Engineers, Pittsfield, Mass., May 29, 1914.

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INFLUENCE OF TRANSFORMER CONNECTIONS ON OPERATION

BY LOUIS F. BLUME

ABSTRACT OF PAPER

In this paper the relative advantages and disadvantages in operation of the more important three-phase transformer connections are discussed. Three conditions of operation are given: First, normal; second, operation of a bank with one phase disabled; third, effect of line grounds on operation.

The paper is not complete, particularly in that high-frequency or switching phenomena are not discussed. Its major purpose is to give a fairly adequate presentation of insulation stresses at relatively low frequencies to which transformers are subject in either normal or abnormal conditions of operation. These frequencies include the fundamental or generated frequency and its harmonics and the natural frequency of the system.

The behavior of three-phase auto-transformers under the various conditions of operation given above is also analyzed.

TRANSFORMERS for use on three-phase systems are in the majority of cases connected either delta-delta or delta-Y, these two being almost universally considered superior to the few other connections which may be used for three-phase transmission. Opinions differ, however, as to their relative merits, and the purpose of this discussion is to analyze some of the factors involved.

Operation in Case of the Disabling of One Phase. In the delta-delta connection, operation can be continued by running open delta after removing the disabled phase, under which condition the bank can handle 58 per cent of its original capacity. When, however, there are two or more delta-delta banks operating in parallel, the advantage of open delta operation of one bank becomes less, on account of the fact that a mutual relation exists between the loads in the two banks. For example, if one phase of one bank is removed, instead of being able to operate the good bank at 100 per cent capacity and the open delta bank at 58 per cent capacity, making a total of 158 per cent (assuming all transformers alike and that 200 per cent was the original

total capacity of the two banks) it will only be possible to derive from the five transformers 133 per cent capacity.[1] When two delta-delta banks are operated in parallel with one open delta bank, a total capacity of 233 per cent instead of 258 per cent is obtainable. Thus it is evident that with increasing numbers of delta-delta banks connected in parallel, the advantage of being able to operate any one of them in open delta decreases. This, however, is not a serious objection, because, by placing the proper amount of reactance in series with the weakened phase, its available capacity can be considerably increased.

Open delta operation of a three-phase core type transformer is, in the majority of practical cases, not possible, on account of the interlinked magnetic structure.

In delta-Y connections, the disabling of one phase renders the whole bank inoperative, except in the case when it is possible to change the voltage of the line connected to the Y side of the transformers. This is feasible if a line transmits power from one bank of delta-Y transformers at one end to another bank of Y-delta transformers at the other end, and operation can be continued in case of the disability of one phase by changing the Y connection to open delta in both step-up and step-down transformers, thus reducing the transmission line voltage to 58 per cent of its original value. Under this condition the capacity of the transmission line and transformers is reduced to 58 per cent of the original value, which is equal to the capacity obtained in the case of operating one delta-delta transformer bank in open delta. When, however, two or more Y-delta banks are operated in parallel, the disability of one phase renders the whole of one bank inoperative.

The Effect of Differences in Characteristics of the Transformers Making up a Transformer Bank. When transformers of slightly different ratios are connected in delta-delta, large circulating currents will result in the delta circuits, depending upon the amount of off ratio and the impedance of the transformers; and when transformers having different impedances are connected for delta-delta operation, the division of load between them will be very unequal. In general, a delta-delta connection is very sensitive to variations in impedances and ratios. A Y-delta bank of transformers is far less sensitive to such variations, and in fact transformers having considerable differ-

1. See article entitled "Delta-Delta Transformer Banks in Multiple," by W. W. Lewis, *General Electric Review*, January, 1912, page 47.

ences in ratio and impedances can be used to make up a Y-delta bank without appreciably affecting the current or voltage division of the phases. From this it is evident that, in cases where a three-phase bank is to be made up of dissimilar units of equal kilovolt-ampere capacity, more satisfactory operation can be obtained by connecting delta-Y than delta-delta. On the other hand, if the kilovolt-ampere capacities of the units are different, the delta-delta connection will probably result in a greater combined capacity than Y-delta, because in the delta-delta banks the currents will divide to a certain extent, at least in proportion to the kilovolt-ampere capacity of the units, whereas in the Y-delta connection the currents in all three phases are equal.

Insulation Stresses

The potential stresses on the insulation at fundamental frequency are worthy of consideration and become particularly important in high-voltage transformers. Under normal conditions of operation, that is, when the connected line is free from grounds, the maximum value of these stresses is equal to 58 per cent of line potential. In the delta connection the minimum value of the insulation stress is equal to 29 per cent and occurs at the middle point of the winding, whereas in the Y connection the stress is zero at the neutral end of the winding, and increases uniformly to its maximum value of 58 per cent at the line end. These stresses are tabulated below for convenience in comparison, together with corresponding insulation safety factors, the latter being based on the assumption that the windings are insulated to withstand a test equal to twice normal voltage.

TABLE I

Insulation Stresses from High-Voltage Winding to Ground, in Three-Phase Connections, at Fundamental Frequency, under Normal Operating Conditions.

	Stresses in per cent of line voltage			Safety Factor		
	maximum	minimum	average	maximum	minimum	average
delta	57.7	28.8	43.2	7	3.46	4.64
Y	57.7	0	28.8	infinity	3.46	7

When one terminal of the transformer is grounded, these stresses are all materially increased. Their values at various portions of the winding are shown in Fig. 1. Here high-potential stresses in the insulation from winding to core in per cent

of the normal line voltage for every portion of the high-voltage winding are plotted as ordinates. The curve shows that the stress in the insulation of delta winding is practically equal to line voltage at all points of the winding, the voltage at the middle point, however, being reduced to 87 per cent of this value. On the other hand, in the Y connection the stress in the winding is graded, being a minimum at the neutral and a maximum at the line end. Three cases are given: Curve *a* shows the condition when the neutral is not grounded; curve *b* shows the condition when the neutral is grounded and when the line is capable of maintaining normal voltage notwithstanding the short circuit produced by a ground on the line; and curve *c* shows the stresses in delta-Y transformers excited on the delta side and operating with a grounded neutral. A particularly large reduction of stress is obtained in the latter case, the maximum never exceeding 58 per cent of line potential. These stresses, together with their corresponding safety factors, are given in Table II.

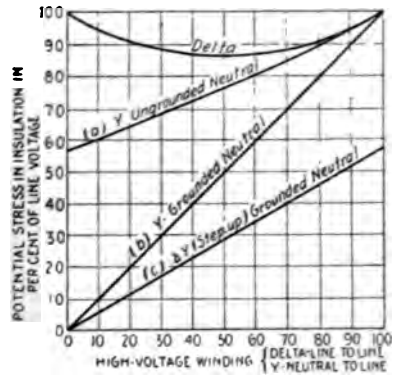


FIG. 1—EFFECT OF GROUNDS ON POTENTIAL STRESSES AT FUNDAMENTAL FREQUENCY ON THREE-PHASE CONNECTIONS

TABLE II

INSULATION STRESSES FROM HIGH-VOLTAGE WINDING TO GROUND, IN THREE-PHASE CONNECTIONS, AT FUNDAMENTAL FREQUENCY, WITH ONE TERMINAL GROUNDED.

	Stresses in per cent of normal voltage			Safety factor		
	minimum	maximum	average	maximum	minimum	average
delta	86.6	100.	93.3	2.3	2	2.1
Y (a)	57.7	100.	78.8	3.46	2	2.54
Y (b)	0	100	50	infinity	2	4
Y (c)	0	7.7	28.8	"	3.46	7

Although the above stresses are relatively small and on that account probably never immediate causes of breakdown, nevertheless it should be borne in mind that stresses of higher frequency are superimposed upon these. It therefore follows that with the transformer connection possessing the smallest average insulation stress at fundamental frequency, or conversely, that

connection which possesses the maximum insulation safety factor (when fundamental stresses only are considered), a greater margin is available for withstanding stresses at higher frequencies. These margins, which are obtained by subtracting the insulation stresses given in Tables I and II from the transformer test voltage (200 per cent of normal voltage), are given in Tables III and IV.

TABLE III

INSULATION MARGINS FOR NORMAL OPERATIONS, IN PER CENT OF LINE VOLTAGE.

	maximum	minimum
delta	171 per cent	142.3 per cent
Y	200	142.3

TABLE IV

INSULATION MARGINS WITH ONE TERMINAL GROUNDED, IN PER CENT OF LINE VOLTAGE.

	maximum	minimum
delta	113 per cent	100 per cent
Y (a)	142	100
Y (b)	200	100
Y (c)	200	142

These tables, however, only roughly indicate that the Y connections, particularly in the case represented by curve *c* of Fig. 1, are capable of withstanding greater stresses at higher frequencies than the delta connection; it would be a true indication provided the insulation is only capable of withstanding twice the line voltage. The table should therefore have been worked out in terms of the actual strength of the insulation instead of the test voltage for which it was designed.

Line Grounds on Isolated Systems. In an isolated system, when a solid ground occurs on the line, the grounded wire is reduced to zero potential and the potentials of the other lines are raised to line potential above ground. If a ground occurs on the line, a considerable distance from the transformers, the charging current flowing through the reactance of the line will cause the potential of the grounded line at the transformer to be somewhat above zero, and since the induced voltage of the transformer will also be somewhat greater than its normal value on account of the reactance drop caused by the charging current (particularly when the transformer possesses high inherent reactance), the free line is raised to a fair percentage above its normal potential above ground. This effect is also somewhat larger than one

would ordinarily assume, on account of the fact that the electro static capacity of a transmission line having one of its line solidly grounded is in the majority of cases considerably greate than when the lines are thoroughly insulated. However, non of these effects is very large, and in general the result of a dea

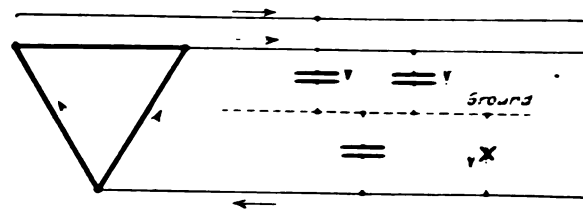


FIG. 2

ground on an isolated system is to bring the other two wires to a potential somewhat greater than normal above ground. The in sulation safety factor has thereby been reduced to a value slightly less than two, and it is evident that the values of insulatio stresses and safety factors given in Tables I and II and the curve in Fig. 1, are not quite correct when transformers are connecte

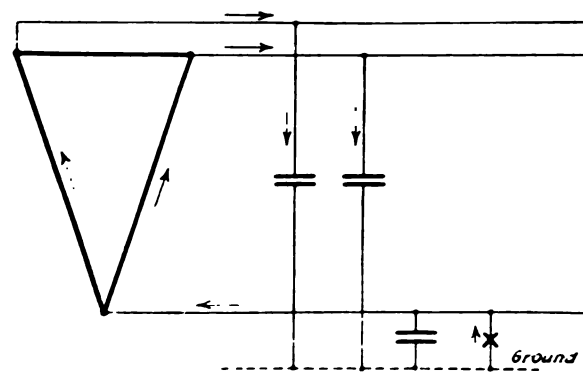


FIG. 3

to transmission lines of considerable electrostatic capacity. I is possible to operate an isolated system with one of its lin solidly grounded without serious risk, and there have been cas of high-voltage, long-distance transmission lines operating i this manner for several hours with a solidly grounded or even broken line.

But when the ground occurring on the line is not a dead ground, an arc results between line and ground which, on account of the fact that it is in series with the electrostatic capacity of the transmission line (see Fig. 2), generally results in an unstable arc or an arcing ground.

General experience with arcing grounds on isolated systems has shown that they are usually accompanied by large rises in potential of transmission line and connected transformers. This rise in potential is shown diagrammatically in Fig. 3.

Such conclusions are corroborated also by the results obtained in the experiments made by Dr. E. J. Berg, and reported in an Institute paper[2] in June, 1908, entitled *Tests with Arcing Grounds and Connections.*

Grounds on a System Having Neutral Grounded. A ground on a system having a neutral grounded, results in a short

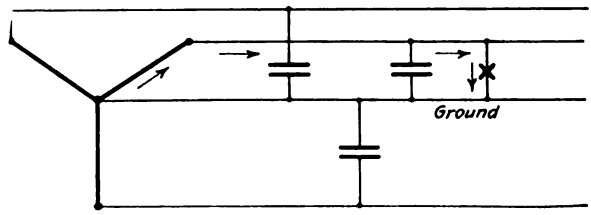


FIG. 4

circuit, and a dynamic current flows, the value of which depends upon the combined impedance of the circuit through ground and impedance of the transmission line and connected apparatus through which the short circuit flows. (See Fig. 4). This results in an impedance drop throughout the circuit and a consequent lowering of the voltage. The resultant arc is in series with the reactance of the transmission line, and since reactance tends to stabilize an arc, the likelihood of an arcing ground resulting is therefore much more remote than in the case of the isolated system.

In general, with the grounded Y system, resonance on account of the electrostatic capacity of the line is not likely, since the line capacity is not in series with line grounds. There is one particular case, however, when resonance may be produced. For example, in a delta-Y system with grounded neutral, suppose

2. TRANSACTIONS A. I. E. E.. 1908, XXVII, Part I, page 741.

one phase on the delta side is burned open, resulting in open d excitation. The high-voltage side of the burned-out phase t constitutes a reactance in series with electrostatic capacity of transmission line and excited by the voltages from the other phases. If the charging current of the transmission line is e to the magnetizing current of the transformer, resonance is tablished at fundamental frequency. However, the increas voltage is limited by the saturation of the transformer; for ample, assuming that the normal flux density of the transfor is 80,000 lines per sq. in. (6.452 sq. cm.), it follows that more t a 50 per cent increase in voltage can hardly be expected. resulting stresses on the insulation are therefore less than tl reached in isolated systems when grounds occur on the line.

If the voltage impressed on the low-voltage side contai

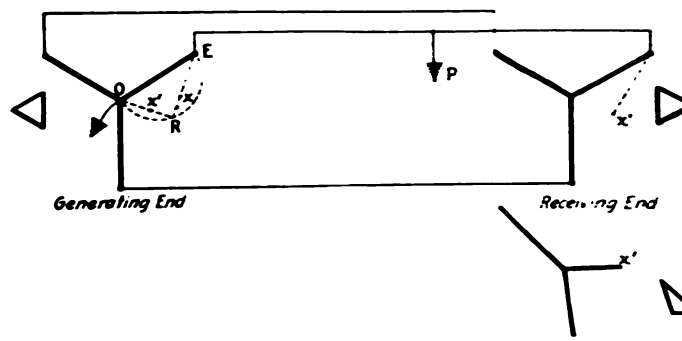


FIG. 5

prominent fifth harmonic, there is a probability of establisl resonance at five times normal frequency, and dangerous v ages built up thereby. However, the likelihood of obtai resonant conditions at five times normal frequency is not great, and moreover the fifth harmonic in impressed volta generally small. Also the importance of this consideratic small on account of the fact that it can only take place v one delta bank is connected to the transmission line and when phase of the low-voltage delta becomes open-circuited.

The effect, upon the distribution of the voltage, of a line gr on a grounded Y system, is shown diagrammatically in Fi The portion consumed by line resistance and reactance br the potential of P to some point X' and the potential OX consumed in overcoming the resistance of the current path f the line ground P to neutral O.

The worst short circuit occurs when a dead ground happens on the line near transformer A, which causes a collapse of the short-circuited phase throughout the system, and a short-circuit current only limited by transformer reactance.

Resistance in Neutral. To reduce the value of this short-circuit current, resistances are often inserted between the neutral point and ground.

A resistance inserted in the neutral causes the neutral o to shift with respect to ground when a ground occurs on the line, or relatively speaking, the ground will shift along the line OX'. If resistance of ground is small compared to resistance at neutral the ground potential in Fig. 5 is X'. A dead ground on the line near the transformers causes the neutral to shift a value equal to $\frac{rE}{r+jx}$, where r equals resistance of neutral and x equals reactance of transformer. It is evident that an increase in potential stress on the remaining phases results.

Assume a transformer with six per cent reactance, and resistance of neutral which will limit the current resulting from a dead ground to three times normal, that is, the resistances and reactances together are equivalent to an impedance of 33 per cent. The reactance of neutral must, therefore, be $\sqrt{(33)^2-(6)^2} = 32.5$ per cent, and the neutral shift will be equal to $3 \times 32.5 = 97$ per cent. *Evidently any resistance inserted in the neutral, if it is to limit currents to values appreciably less than those obtained when the neutral is dead grounded, must be capable of withstanding practically normal phase potential.* Moreover, the purpose of grounding the neutral is destroyed, for a neutral shift of 75 per cent or more of the phase voltage means that the free lines have been raised to practically full line potential above ground.

A neutral will therefore remain stable only when the IR drop produced across the neutral resistance by the short-circuit current is small compared with the line voltage. Practically all the voltage must be consumed by the resistance of the ground and resistance of neutral in series. From this we can conclude that *a neutral with resistance will hold the neutral fairly steady and prevent undue rises in potential, provided the line grounds do not occur with resistance* (including line resistance to point of ground) *less than ten times the resistance in the neutral.*

The ratings of the resistance inserted in the neutral for various limiting values of short-circuit current are given in Table V. These are worked out on the basis of transformer reactance

equal to six per cent, resistance one per cent, and on the assumption that the short-circuit current is limited only by the resistance in the neutral and the impedance of the transformers.

TABLE V

Short-circuit current	Volts across neutral in per cent of transformer normal voltage	Rating of kv-a. resistance in per cent of normal kv-a. of one phase
16.4 times normal	0	0
12 " "	57	644
10 " "	70	700
5 " "	90	450
3 " "	94	280
2 " "	96	196
1 " "	100	100
0.5 " "	100	50

The size of the resistance will also depend upon the length of time short circuit is maintained. For example, if the system is protected by relays which disconnect the apparatus in two minutes, the resistance must be designed to dissipate the power given in the table for this period of time.

Grounding the Neutral at Receiving End. In the preceding discussion the neutral at the generating station was in every case considered grounded. However, when the neutral of the step-down transformers at the far end of the transmission line is grounded, and the neutral at the generating station isolated, a different condition exists. In this case, when one line near the step-down transformers becomes grounded, one phase is short-circuited thereby, and current flows as indicated by the arrows in Fig. 6. If the step-down transformers are small compared with the kilovolt-ampere capacity of the system to which they are connected, the line voltage is not appreciably affected by this short circuit, although the grounded line assumes ground potential. Line potential is therefore impressed across two phases, as indicated in *a* of Fig. 6, and the ungrounded lines assume a potential of practically line voltage above ground. The currents flowing are single-phase and produce in each phase a reactance drop equal to *ab*, that is, phase voltage.

If, on the other hand, the step-down transformers have a kilovolt-ampere rating comparable with the rating of the transformers at the generating station, the resulting short-circuit currents are severe enough to reduce the line potential at the step-down transformers very materially. On that account

they are not as liable to an increase in induced potentials and potential stresses from winding to ground.

Complete protection, however, is not given in this case to the step-up transformers, for if a ground occurs near the generating station, the short-circuit currents must flow through the ground between the generating station and receiving end, in which case the voltage drop on the ground and in lines may be sufficient to limit the short-circuit currents, and therefore decrease the reactance drop within the transformers. Under this condition, the terminals of the step-up transformers will assume a potential above ground equal to line voltage.

Auto-Transformers. Wherever it is desired to interconnect two high-voltage systems of not very great voltage difference,

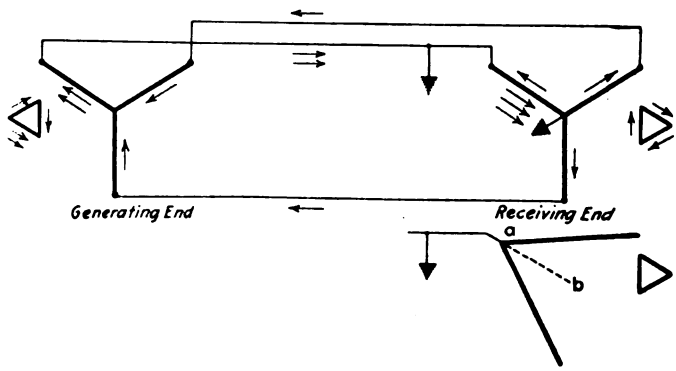


FIG. 6

as, for example, 100,000 volts and 60,000 volts, the use of Y-connected auto-transformers is cheaper than transformers, because a large saving is effected due to the fact that the rating is only a fraction of the power which the auto-transformer can transmit from one system to the other. Since reduction in rating is only material when the connection is Y, a delta-connected auto-transformer is seldom used. But when the transformation ratio is three or more, the saving in the use of auto-transformers instead of transformers is too small to outweigh the disadvantages which their use entails.

As auto-transformers are cheaper from the standpoint of first cost, it is of interest to investigate potential stresses at normal or fundamental frequency resulting from abnormal conditions, as line grounds, etc., in order to determine their

reliability and therefore their eventual cost. These insulat stresses depend upon whether the system is isolated or groun Y, and whether the neutral of the auto-transformer is ground There are four cases:

Case I. System Isolated, Auto-Transformer Neut Ungrounded (See Fig. 7)

(a) A triple-frequency e.m.f. exists from line to neut increasing the induced potential stress from 20 to 50 per ce depending upon the flux density in the iron. The insulat stress from winding to core is increased at the neutral, but at the line ends of the winding. The presence of the tri frequency voltage, therefore, is not serious, for although average potential stress on the insulation is increased, maximum stress is not affected.

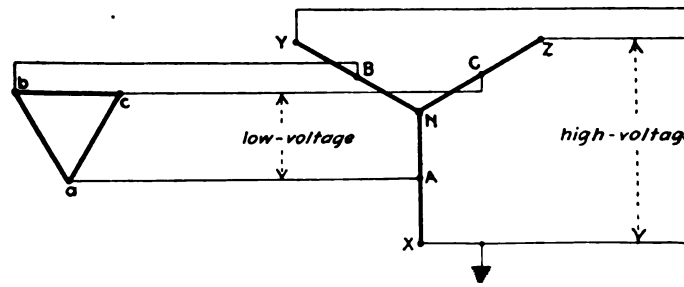


Fig. 7—System Isolated, Auto-Transformer Neutral Ungroun

(b) A ground at X (Fig. 7) places the low-voltage line and C at a potential above ground approximately equal to high-voltage + 0.42 low-voltage.

Thus, if the auto-transformer steps up from 60,000 v to 100,000 volts, a solid ground existing on the high-volt line raises the potential of the low-voltage line to 81,000 v above ground.

Case II. System Isolated, Auto-Transformer Neut Grounded (Fig. 8)

(a) The triple-frequency e.m.f. which is present as in I, is now exerted across the line insulation to ground. Th particularly dangerous if the auto-transformer is connecte systems having considerable electrostatic capacity. Elec static capacity between lines and ground causes a char

current in which the third harmonic is prominent, which reacts on the triple-frequency e.m.f., intensifying it. Potential peaks equal to three times normal can easily be obtained in this way at ordinary densities, although at very low densities and at saturation densities, the danger is less. The charging current necessary to produce these voltages is not large.

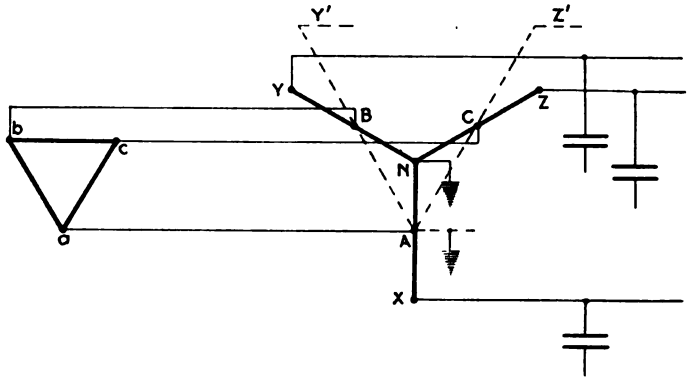


FIG. 8—SYSTEM ISOLATED, AUTO-TRANSFORMER NEUTRAL GROUNDED.

(b) A ground at A causes NA to collapse, NA and X are reduced to ground potential and the remaining phases receive open delta excitation at 1.73 normal flux density. This is shown by the dotted lines in Fig. 8. B and C are placed at low-voltage potential above ground.

(c) A ground at X produces the same result as a ground at A.

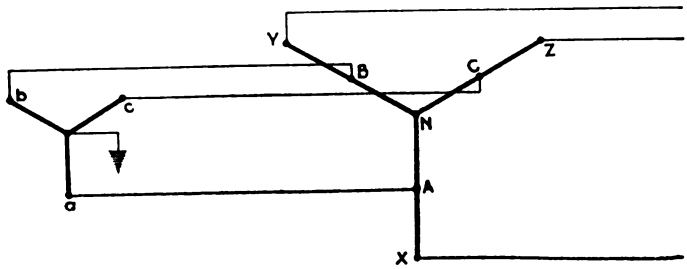


FIG. 9—SYSTEM GROUNDED, AUTO-TRANSFORMER NEUTRAL UNGROUNDED

CASE III. SYSTEM NEUTRAL GROUNDED, AUTO-TRANSFORMER NEUTRAL ISOLATED (SEE FIGS. 9 AND 10)

(a) Triple-frequency voltage present as in Case I. Since the neutral is isolated, there is no danger of the triple-frequency voltage being intensified.

(b) A ground at *A* short-circuits one phase of the low-voltage system.

(c) A ground at *X* results in distortion of and increase in induced voltage in the auto-transformers, as shown in Fig. 10. The low-voltage system does not receive an abnormal voltage or abnormal insulation stress.

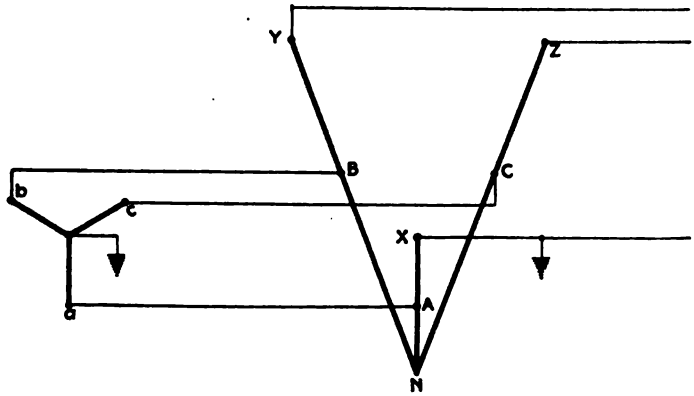


FIG. 10—SYSTEM GROUNDED, AUTO-TRANSFORMER UNGROUNDED, SHOWING EFFECT OF DEAD GROUND OCCURRING ON LINE

CASE IV. SYSTEM NEUTRAL GROUNDED, AUTO-TRANSFORMER NEUTRAL GROUNDED (SEE FIG. 11)

(a) Triple-frequency e.m.f. is much reduced because triple-frequency currents can flow through ground connections. The

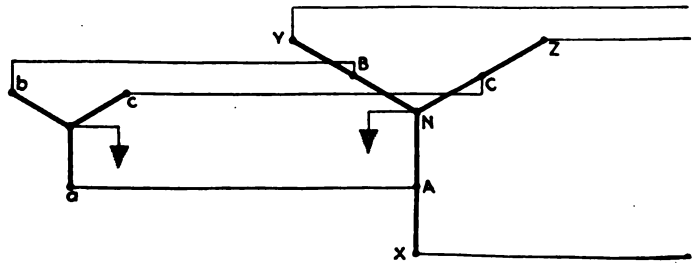


FIG. 11—SYSTEM GROUNDED, AUTO-TRANSFORMER NEUTRAL GROUNDED.

reduction in triple-frequency e.m.f. depends somewhat upon the resistance of the ground circuit.

(b) A ground at *A* short-circuits one phase of the low-voltage circuit.

(c) A ground at X short-circuits one phase of the auto-transformer and one phase of the low-voltage circuit through the auto-transformer reactance. The potential of B and C cannot rise above normal values.

In the above cases, single-phase auto-transformers were assumed, although the same results are obtained in three-phase shell type units. In the three-phase core type transformers, the triple-frequency e.m.f. is reduced to negligible proportions on account of the interlinked magnetic circuit. Moreover, in the case of a grounded neutral, when a ground occurs on the line, the interlinked magnetic circuit resists the collapse of one phase, by causing heavy currents to flow in all three phases. The value of this current depends upon the resistance of the ground, a dead ground in the majority of cases causing currents comparable to short-circuit currents.

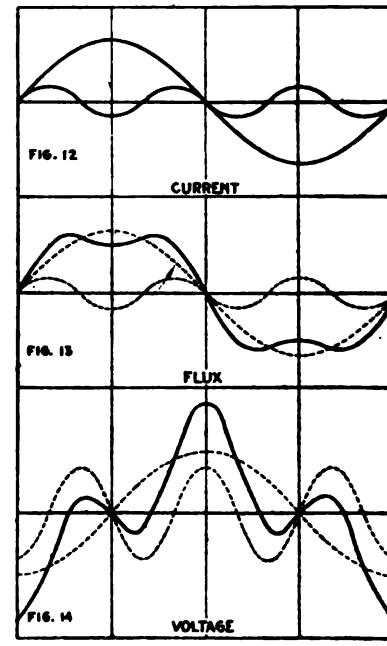
If the neutral of the system is grounded through a resistance to limit short-circuit currents, excessive currents are prevented when a ground occurs on the line. However, in that case the neutral will remain stable only for high-resistance line grounds. If a dead ground occurs on the line, full phase voltage is impressed across the neutral resistance and potential stresses will exist similar to those occurring in isolated delta systems. In general, it may be said that the grounded neutral, with a resistance to limit the current flow, acts like a solidly grounded system as long as grounds of high resistance only occur on the line. When a dead ground occurs, the resulting potential stresses will be practically the same as if the system were operating ungrounded.

It should be borne in mind that the conditions in the majority of practical cases considerably depart from those cited here. For example, in the case shown by Fig. 7, the normal flux density may be so high that the magnetizing current required for 73 per cent increase in voltage will be so great as to cause a line reactance drop sufficient to reduce considerably the voltages applied to the transformers. However, the diagram applies rigidly to all cases where the normal flux density is made low enough so that, when a ground occurs, the cores will not be supersaturated. Similarly, the conditions shown by Fig. 10 will not occur in practise on account of the excessive magnetizing currents resulting.

It is evident from the analysis of the four cases given above, that high-voltage auto-transformers should not be generally used

without solidly grounding the neutrals. Grounding the neutral necessitates the elimination of the triple-frequency e.m.f., which may be done either by using the three-phase core type structure or by having a Y-delta transformer with grounded neutral connected to the same system. The latter method, is, however, questionable, because the safety of the auto-transformer then depends upon proper operation of another piece of apparatus.

If such precautions are taken, auto-transformers should operate successfully, although they still possess the objection that the high-voltage and low-voltage systems are rigidly connected together by means of an electrical conductor, whereas a transformer connects the systems in a more flexible manner, *i.e.*, magnetically. Due to this, a disturbance occurring on one line is likely to be felt on the other, when auto-transformers are used. With tie-in transformers, operating on isolated systems, it is possible for grounds to occur on line without disturbing the operation or increasing the stresses on the other lines.



FIGS. 12, 13, 14—CURRENT, FLUX AND VOLTAGE RELATIONS IN Y-CONNECTED AUTO-TRANSFORMERS

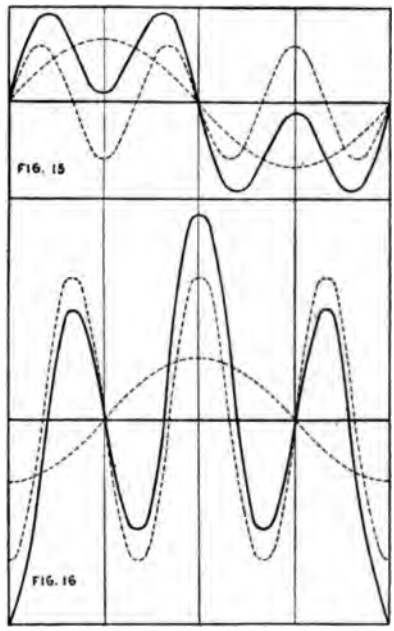
THE THIRD HARMONIC IN THE Y CONNECTION

Due to the fact that the permeability of iron decreases as the flux density increases, the wave shape of magnetizing current in a transformer is different from the wave shape of the electromotive force. When the impressed electromotive force is a sine wave, the magnetizing current shows a peak, which, when analyzed, resolves itself into a prominent third harmonic and higher harmonics of lesser values.

In the Y connection, third-harmonic currents and currents having frequencies multiples of the third cannot flow, on account of the fact that these currents in the three phases would be in

phase with each other, and to permit them to flow, a circuit must be provided at the neutral.

Owing to the fact that the triple harmonic current necessary for sinusoidal excitation cannot flow in Y-connected transformers the resulting flux wave takes a flattened form, which, when analyzed, resolves itself into the fundamental and a triple harmonic. The flux wave under this condition is shown in Fig. 13, and the corresponding voltages induced from line to neutral are given in Fig. 14. For average operating densities in transformers, the triple-harmonic voltage is approximately 60 per cent of fundamental voltage.



FIGS. 15, 16—ANALYSIS OF THIRD HARMONIC INTENSIFICATION IN Y AUTO-TRANSFORMERS

When the neutral of the auto-transformer is grounded, the triple harmonic together with the fundamental is impressed between line and ground across the capacity of the connected transmission line. A triple-frequency charging current flows into the line and through the auto-transformer windings. The phase angle of this current with reference to the fundamental magnetizing current is shown in Fig. 12. This triple-frequency current constitutes an additional magnetizing current in the auto-transformer, and a comparison with Fig. 13 shows that it is in phase with the triple-frequency flux which was produced by the original sine wave magnetizing current. Therefore the triple-frequency current acts to increase the triple-frequency flux and a corresponding intensification of triple voltage ensues. The increased triple-harmonic voltage results in a greater triple current, which causes a further increase in flux. This intensification is only limited by the saturation of the transformer. Figs. 15 and 16 show flux and voltage waves in which the third harmonic has reached its maximum value. It is evident that under such conditions of operation the core loss of the transformers will

be about three times normal and the insulation stress about fou times normal.

Conclusions

The following are the more important conclusions which ma be drawn from this paper:

First: Isolated systems are subject to greater insulatio stresses than grounded systems.

Second: In grounded systems, the average insulation facto of safety is greater than in isolated systems under similar condi tions of operation.

Third: In isolated systems, the stresses at lower frequencie under certain conditions, may reach values sufficiently high t injure or destroy the transformer and other apparatus connecte to the system.

Fourth: In an isolated system, a ground on the line is mor likely to result in an arcing ground or intermittent arcs than in grounded system.

Fifth: A ground on the line in a solidly grounded system reduces the potential of the system with respect to ground whereas in the isolated system, a ground on the line increases th potential of the system with respect to ground.

Sixth: A resistance inserted between neutral and ground t limit the value of short-circuit current increases thereby the in sulation stresses resulting from line grounds.

Seventh: If it is desired to limit the value of potential a fundamental frequency above ground of any part of the system t 57 per cent of line potential, it is necessary to solidly ground th neutrals at both receiving and generating ends of transmission line

Eighth: If receiving transformers of relatively small kilovolt ampere capacity are connected with grounded neutral to an other wise isolated system, they are liable to severe short circuits and the grounded neutral only partially protects the syster from potential rises.

Ninth: In Y-connected auto-transformers, it is dangerous t operate with isolated neutral except when the ratio of trans formation is nearly unity.

Tenth: In Y-connected auto-transformers, it is dangerous t operate with isolated neutral except when the entire syster is isolated.

Eleventh: In Y-connected auto-transformers, it is dangerou to operate with grounded neutral unless the triple-harmonic volt age between line and neutral is eliminated or kept negligibly smal

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A STUDY OF SOME THREE-PHASE SYSTEMS

BY CHARLES FORTESCUE

ABSTRACT OF PAPER

The star-star, delta-delta, delta-star and star-delta connections are taken up in order and their individual peculiarities and characteristics, precautions that must be taken in operation to avoid trouble, and where and when the system may be grounded with best results, are discussed.

The question of delta-delta vs. delta-star is considered:

(1) For moderate voltages the delta-delta system has the advantage on account of its greater flexibility.

(2) For high voltages the delta-star connection is preferable, chiefly on account of its greater strength and lower cost. There is a probability that a delta-star bank of transformers will cause less disturbance in switching than one that is delta-delta connected.

(3) There are much greater possibilities of development in transformers designed for delta-star connection than for any other.

(4) Past and present practise upholds the use of the delta-star connection in preference to the delta-delta for high-voltage transmission.

IT IS proposed in this paper to study several common methods of connecting transformers for use on polyphase systems, with the view of displaying the advantages and disadvantages of each, showing under what conditions they may be used to the best advantage.

STAR-STAR CONNECTIONS

It is well known that on account of the shape of the hysteresis loop of transformer iron, the m.m.f. required to produce a sine wave of induction in a magnetic circuit of uniform cross-section made of iron will not be of simple sine wave form, but will include a third-harmonic wave; and vice versa, if the third harmonic be absent from the m.m.f. it will appear in the wave form of the induction. In the primary of a star-connected group of transformers the sum of the three currents flowing towards the neutral point must be zero; consequently, the third harmonics of the magnetizing currents in each phase, being of the same phase, are

suppressed and a third harmonic appears in the e.m.f. between the neutral and the supply mains.

The presence of the third harmonic in the e.m.f. between the neutral and mains of the primary circuit does not materially affect the e.m.f. between lines in the secondary circuit, but a load cannot be taken off between the neutral point and lines because this e.m.f. is unstable, that is to say, the neutral point will shift. The reason for this is evident and needs no explanation. If the neutral point of the secondary circuit be grounded, the secondary line terminals will have a third-harmonic pulsation to ground which may cause serious disturbances in neighboring telephone circuits.

In single-phase transformers and three-phase shell-type transformers this third-harmonic component of the wave form may be entirely eliminated by using an interconnected star secondary winding; and if care be taken properly to interlace the windings, the neutral point will be stable and a load may be taken off the secondary circuit between the neutral and lines.

If the neutral point of the primary winding be connected to the neutral point of the generator the secondary neutral point will be stable, and loads may be supplied between the neutral point and the lines; but, since the generator itself may have a third-harmonic component in the e.m.f. between neutral and terminals-it is not advisable to ground the neutral point of the secondary winding. If, however, the secondary winding be in interconnected star, the neutral point may be grounded without causing trouble.

In three-phase transformers of the form of construction known as core-type, that is to say, transformers with interlinked magnetic circuits, this same interchange of m.m.f. takes place between the phases, so that each phase has part of the required m.m.f. supplied from the other two phases during a portion of the cycle. The sum of the three magnetic fluxes must be zero and therefore the sum of the three induced e.m.fs. must also be zero, and thus the neutral point is the centroid of the primary voltage triangle. In such transformers, due to the above-mentioned interchange of third-harmonic m.m.f., there exists a third-harmonic leakage field in the air external to the coils. The neutral point will be symmetrical, even with wide differences in the permeability of the cores, the required m.m.fs. for the three cores

being supplied in the proper relation by the three primary windings. The magnetizing currents in three-phase transformers of this type which are unsymmetrical have third-harmonic components, which are in three-phase relation and produce unlike waves in the three phases.

If a load be taken off the secondary of a three-phase transformer of the type under discussion, a leakage field is set up in the coil spaces between the loaded phase and the other two, which is usually large. The regulation of such transformers for loads between the neutral and lines is not usually good. The condition is similar to the effect of loading one side of a single-phase core-type transformer connected for three-phase distribution which had not been designed with cross-connected secondary windings. Interconnection of the primary or secondary windings is one remedy for this trouble.

If a three-phase transformer or group of single-phase transformers be intended to operate with the neutral of the primary connected to the neutral of the generator, the primary winding should not be interconnected, because thereby the impedance to the flow of the third-harmonic current set up by the third-harmonic component in the generator e.m.f. wave between neutral and terminals is rendered very small and these currents may be large enough to cause undue heating.

In the straight star-connection with single-phase transformers, the voltage stress per turn on the windings is quite high on account of the excessive peaking of the e.m.f. between neutral and lines. The core loss of the transformers is usually lower than for a sine wave e.m.f., even though the effective value of the neutral to line e.m.f. is more than 57 per cent of the e.m.f. between lines. Formerly it was considered a grave disadvantage of this connection that a short-circuited unit would cause 73 per cent increase in stress on the other two. It is not probable now that such a condition could exist without tripping the breakers, since this increase in voltage with the steel now used in transformers would result in a magnetizing current having an effective value several times the full-load value of current.

The advantage of the star-star connection of single-phase transformers is in its simplicity and low cost. It is not suitable for four-wire three-phase distribution, nor should it be operated with the neutral grounded. The transformers are subjected to an undue stress between layers and between coils on account of the distorted e.m.f. between neutral and lines.

If the neutral of the primary be connected to the neutral of a generator which has no third-harmonic component the connection may be used for four-wire three-phase transmission with or without the neutral point grounded.

If, on account of the desirability of grounding the neutral point, it is found necessary to interconnect the windings, the advantage of simplicity and low cost is lost, to a great extent.

Three-phase transformers star-star-connected may be used with or without the neutral grounded, for three-phase three-wire transmission. Light loads may also be taken off between neutral and line. Interconnecting the low-tension winding does not involve much trouble, but it is simpler to connect this winding delta, which produces the same result in a simpler manner.

Star-star-connected three-phase transformers have the same advantage as single-phase transformers connected in the same manner, and the stress to which the insulation is subjected may be reduced to a smaller value for a given voltage between terminals than with any other connection; this advantage, however, is of little consequence when the line e.m.f. is low. They have the additional advantage that the e.m.fs. between neutral and lines do not have a third harmonic.

Delta-Delta Connection

This connection is the most widely used of all three-phase connections, and is recommended for moderately high voltages on account of its extreme flexibility.

The third harmonic and its multiples are eliminated in the terminal e.m.fs. of a symmetrical star-connected generator, and if the three delta-connected transformers are alike in design and magnetic characteristics they will be absent in the secondary e.m.fs. Differences in characteristics of the transformers are corrected in this connection by interchange of m.m.f. through the secondary windings. A marked dissymmetry in the bank of transformers may cause a third-harmonic component in three-phase relation to appear in the secondary e.m.f.s between lines; but the usual third-harmonic distortion characteristic of the secondary e.m.f. of single-phase transformers is not present in the e.m.f. between phases, due to the fact that the delta-delta connection affords a low impedance path to the flow of current set up by such a component, thereby automatically eliminating it. In three-phase transformers of the form known as core-type, the interlinking magnetic circuits of the three phases somewhat

modify the interactions between the three phases, but the differences in action from single-phase transformers connected in delta are trifling.

The chief advantage of the delta-connected group of single-phase transformers lies in its flexibility. If one of the transformers in a group fails, the other two are able to supply power at a diminished rating, the only change being the cutting out of the defective transformer, which may be done without interference with the operation of the other two.

The stresses to which the insulation is subjected are higher than in the star connection, and there is no means of grounding the neutral except through the intermediary of an interconnected star group of single-phase auto-transformers or a three-phase auto-transformer, or some such device, provided with a star connection.

Star-Delta and Delta-Star Connection

These methods of connecting transformers have been the subject of a good deal of controversy, and have suffered through misapplication. It was pointed out that in the star-star connection it was necessary to interconnect the primary winding to eliminate the distorting third harmonic and to obtain a stable neutral point; this is effected in the delta-star connection at a minimum cost, and with a maximum degree of stability of the neutral point. It is in reality a more direct transformation than the delta-delta connection; since there can be no interchange of m.m.f. between phases, the secondary neutral to line e.m.f. is the same as that obtained with single-phase transformation and may contain a trace of third harmonic as in single-phase transformers due to the reactive drop of the exciting current.

The three-phase core-type transformer with delta-star connection has a stable neutral point and also on account of the interlinked magnetic circuits the secondary neutral to line e.m.f. is absolutely free from third harmonic. The three-phase shell-type does not differ materially from three single-phase transformers.

The star-delta connection has some very interesting peculiarities, lack of understanding of which has led to its improper use, resulting in troubles which have been considered as the fault of the connection, rather than of the individuals who misapplied it. In this connection the sum of the secondary induced e.m.fs. must be zero on account of the delta-connected secondary, consequently the neutral point of the primary star connection

must be the centroid of the primary e.m.f. triangle, except for the slight distortions caused by the drop due to the exciting currents in the windings. It has already been pointed out that a third-harmonic component is required in the m.m.f. wave to produce a sine wave of induction. If, therefore, the primary is star-connected, from what source is this third-harmonic m.m.f. supplied? The answer is that it is supplied to each phase as required by the other two through the secondary delta-connected winding, so that there exists a circulating third-harmonic magnetizing current in the delta of transformers connected in this manner, which is equal in magnitude and time phase to the equivalent component in the normal single-phase secondary exciting current of the transformers. The effect of differences in the magnetic characteristics of transformers so connected is to cause slight dissymetry in the secondary e.m.f. waves between lines, which is due to third-harmonic components in three-phase relation which appear in these e.m.fs.

If the neutral of a star-delta-connected bank of transformers be connected to that of the generator supplying the transformer the result will be a short-circuit so far as the third-harmonic component of the generator between neutral and terminals is concerned, the flow of third-harmonic current being limited only by the impedance of the transformers, and very serious heating may result, both to the generator and to the transformer. Since the neutral of the transformer is stable there is no necessity for connecting it to that of the generator, and if it is desired to ground the primary system this may be done most advantageously by grounding the neutral point of the bank of transformers.

The delta-star-connected three-phase transformer, or bank of transformers, is suitable for three-phase transmission and distribution with both three and four wires. A load taken off between neutral and line will cause the neutral to shift only an amount equal to the impedance drop of the transformer supplying the loaded phase. In four-wire three-phase systems, where the e.m.f. is stepped up through delta-star transformers, and three-phase power is supplied through star-delta step-down transformers, the latter, if their neutral be connected to the neutral, serve as balancers for loads taken off between neutral wires and lines. Fig. 1 will suffice to explain this action of the star-delta-connected bank of transformers. A small bank of star-delta-connected transformers in the neighborhood of a heavy unbalanced load taken off between neutral and lines at the end of a long feeder,

is, on account of this characteristic, liable to be overloaded if its neutral be connected to the neutral wire.

An interesting peculiarity of these connections is that when the wave form of applied e.m.f. is not a sine wave, a peaking harmonic in the e.m.f. across the lines will produce a flattening harmonic in the e.m.f. between neutral and lines, and vice versa, although the effective values will be in the ratio of 1 to $\sqrt{3}$, as for a sine wave; as a consequence the core loss of a three-phase star-delta-connected transformer may have different values when measured on the star side and delta side, when the form factor of the impressed wave differs from that of a sine wave.

The star-delta and delta-star connection has all the advantages of the star-star connections without their grave disadvantages; as pointed out before, when the e.m.f. is low, there is no

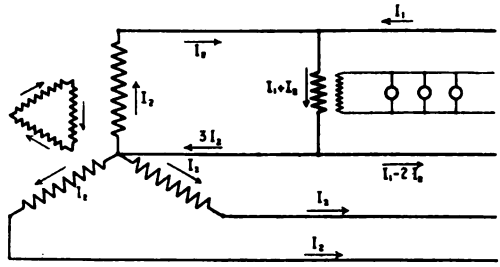

FIG. 1—ILLUSTRATING THE REGULATING EFFECT OF A STAR-DELTA-CONNECTED GROUP OF TRANSFORMERS ON A THREE-PHASE FOUR-WIRE SYSTEM.

inherent advantage in the star connection; actually there may be decided disadvantages. There is no advantage in supplying a single-phase load from the neutral point of a generator, on the contrary the single-phase output of a three-phase generator is greatest when the power is supplied from two terminals. The delta-star connection permits of this and therefore increases the unbalanced capacity of the whole system. Consequently, even should it be possible to entirely eliminate the third harmonic from the e.m.f. wave between the neutral and terminals of a generator, the star-star connection is hopelessly out of the running when it has to compete with the delta-star connection. In three-phase transformers the delta-star connection is the most economical way of obtaining good regulation between neutral wire and lines in a three-phase four-wire system.

Discussion of Delta-Delta and Delta-Star Systems

In the following part of this paper the discussion will be confined to the last two systems of three-phase connections; the proper field for each will be pointed out and the reason given for the selection.

For three-phase transmission at moderate voltages, say up to 33,000 volts, the advantage lies with the delta-delta connection for single-phase transformers, on account of its greater flexibility and because the failure of one unit in a bank interrupts service for only the short length of time required to cut out the defective unit, operation being continued with the transformers connected in V at a reduced rating.

For three-phase four-wire distribution the delta-star and star-delta-connected transformers are most suitable. It may not be out of place here to sound a note of warning in connection with supplying single-phase service from three-phase sources grounded or ungrounded. In a single-phase transformer connected to a three-phase system, the secondary winding has a potential determined by the mean potential of its primary winding and the relative capacity between primary and secondary and between secondary and ground. An ungrounded secondary winding which is disconnected from its wiring may have quite a high potential due to this effect. A preferable way of supplying house lighting from a three-phase line would be by means of a three-phase step down transformer or bank of single-phase transformers having secondaries connected in star-delta or interlinked six-phase, then if the supply circuit were grounded at the neutral point, the secondary circuit could be operated with safety ungrounded. The practise of running single-phase feeders from a three-phase supply to outlying districts for the purpose of supplying lighting service is bad in so far as when the secondaries are grounded it is liable to interfere with telephone service.

Turning our attention now to three-phase transmission at voltages above 44,000 volts, the problem of insulating begins to assume importance. Figs. 2 and 3 are potential diagrams of delta-delta step-up and step-down transformers and delta-star step-up and star-delta step-down transformers. The point O, the centroid of the potential triangle, is at zero potential; the potential of any portion of the winding of any phase is given by the distance of the equivalent point on the potential diagram from the centroid. The e.m.fs. and instantaneous

potentials are given by the projection of the points A B C, a b c on a given line passing through O, the triangle A B C, it being considered as rotating about O so as to make one complete revolution per cycle. Comparing these two potential diagrams, it will be apparent that the high-tension winding of the delta-star transformer is subject to lower average stress than that of the delta-delta, varying in the first connection from 0 to 57.7 per cent of the line e.m.f. and in the second connection from 28.8 per cent to 57.7 per cent of the line e.m.f.

The tendency of any connection to give trouble during switching will probably depend largely on the amount of potential energy stored in the system under normal operating conditions. The high-tension windings of the transformers

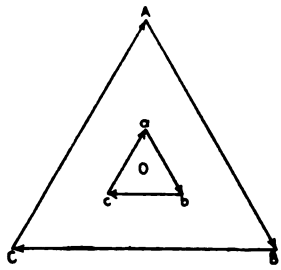

FIG. 2—POTENTIAL DIAGRAM OF DELTA-DELTA CONNECTED BANK OF TRANSFORMERS, NORMAL OPERATION.

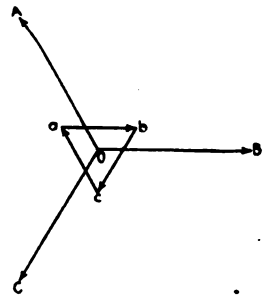

FIG. 3—POTENTIAL DIAGRAM OF DELTA-Y OR Y-DELTA CONNECTED BANK OF TRANSFORMERS, NORMAL OPERATION.

in both connections will have about the same capacity to ground, the tendency being for higher values in the transformers for the delta-delta connection. If v be the effective value of the e.m.f. between lines, the maximum amount of energy stored in the dielectric will be in the case of the delta-delta connection for each transformer $\frac{CV^2}{6}$, and in the case of the delta-star connection it will be $\frac{CV^2}{9}$ for each transformer, the value C being the total capacity of the high-tension winding of each transformer to ground.

It follows in consequence that there will probably be fewer disturbances caused in a transmission system when a star-

delta bank is switched on and off the circuit than when a delta-delta bank of the same capacity is switched on and off; and therefore the insulation stresses due to switching in the star-delta connection will be correspondingly smaller than in the delta-delta connection.

The same relations hold true for any conditions that may arise in operation which causes the breakers to open, such as a ground on the line, short circuits between phases, etc. In every case the energy stored in the dielectric is less for the star-delta-connected group than for the delta-delta-connected group.

The dangers arising from switching are caused not so much by the rapid interruption of large currents (for as a matter of fact the rate of diminution at the instant of interruption is not very much greater than if the breaker remained closed), as because, after the current has ceased, the potential energy in the two systems, that is, the disconnected bank of transformers and transmission line, becomes changed into kinetic energy, setting up oscillations in the two systems which produce differences of potential at the disconnecting points sufficient to cause them to arc over. These abrupt changes in condition set up other trains of oscillation which are superimposed on the first, resulting in abnormal stress on the insulation of the transformers.

When the line is disturbed by lightning, the capacity of the transformers will have little to do with the severity of the disturbance. The charge due to a thunder-cloud, when released, sets up waves which on striking the transformers cause a high stress between adjacent turns of the windings, particularly those near the terminals. A large capacity between adjacent turns will tend to reduce the severity of these stresses. In the star high-tension winding the large wide conductors tend to large values of capacity between adjacent turns, which is the condition required for reducing the stresses.

The delta-star grouping has the advantage from an insulation standpoint even if the neutral point is not grounded. With a grounded neutral point the insulation stress is still further reduced, an advantage which cannot be obtained with the delta-delta system without auxiliary star-delta transformers.

The mechanical stresses due to short circuit will be the same for both systems, but delta high-voltage windings are not so well adapted to withstand mechanical shock as the stauncher windings for star connection. It may therefore be stated that,

with equal mechanical support, the delta high-voltage winding will be mechanically weaker than the corresponding star winding.

Considering the two systems from the point of view of cost, let the cost of winding the coils be considered first of all. The coils used in all power transformers of large capacity are discoidal, sometimes termed pancake coils, and consist of spirally wound flat copper ribbon conductors insulated with sleeves or strips of micanite or other insulating material. To enable the workman to produce a servicable coil the conductor must be large enough to hold down the sleeves or layers of insulating materials, otherwise the coil will be "mushy". However carefully a "mushy" coil may be clamped up and treated it can never be as strong mechanically as one more solidly constructed of heavier conductor. More care is therefore involved in winding such coils, in their preparation for treatment and in their handling after treatment, during assembly. The cost per turn per coil is therefore higher, as is also the cost of treatment and handling per coil. There are 73 per cent more turns in a complete delta winding than in a star winding, and an equivalent larger number of coils. The cost of the complete winding will therefore be considerably more for the delta than for the star system.

In assembling, each coil has its own individual insulation; each lead must be tied to its proper position. The coils in a group must be placed in position one by one during assembly and the connections soldered. There are therefore more operations in the assembly of a delta winding than in that of a star winding and the coils have to be handled with more care. The cost of assembly will therefore be higher for the delta-connected than for the star-connected transformers.

Since the conductor to be insulated is smaller in the transformers of the delta group than in those of the star group, the insulation will occupy relatively more space in the former than in the latter, with the result that the dimensions of the transformers for delta connection will be larger and require more active material than those for the star connection.

A transformer designed for delta-star connection is less costly to manufacture than one designed for delta-delta connection. The high-tension wiring of a group of star-connected transformers is simpler than that for one of delta-connected units, which is no inconsiderable advantage with high transmission voltages.

Possibilities of Development

The above discussion applies to present standard practise. Considered from the point of view of future development, the advantage is all with the delta-star and star-delta connections. Thus, for example, the worst condition of stress in the transformers arises when one line becomes grounded. Figs. 4 and 5 are the potential diagrams for such a condition. The delta group has a maximum stress varying from line voltage to 87.7 per cent of the line voltage; in the star group the maximum stress varies from line voltage down to 57.7 per cent of the line voltage. If full advantage be taken of this difference, the transformer for star connection will be lowered still further in cost.

With the advantage afforded by grounding the system at

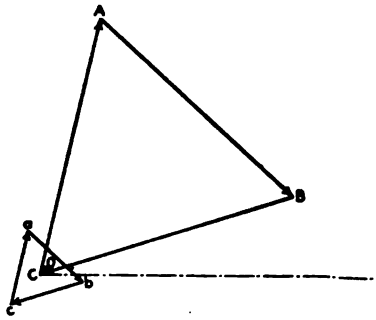

Fig. 4—Potential Diagram of Delta-Delta Connected Bank of Transformers—One Line Grounded.

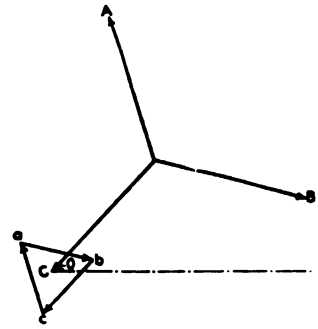

Fig. 5—Potential Diagram of Delta-Y or Y-Delta Connected Bank of Transformers—One Line Grounded.

the neutral point, the star-connected group may be manufactured at a very much lower cost than the delta-connected group.

As improvement in methods of switching will enable the manufacturer to take further advantage of the lower stress to which the star-connected group is subjected under operating conditions, considerable development may therefore be expected in this direction in the future.

Past and Present Practise

In view of the fact that the largest and most successful power transmissions in America are operated with delta-star step-up and star-delta step-down transformers, and that several among them, together with a large number of smaller power companies,

NAME	Operating voltage	Frequency (cycles)	Capacity of plant (kilowatts)	Beginning of operation	Phases	Conn. Low tension	Conn. High tension	Y-grounded direct or through resistance	Conn. Low tension	Conn. High tension	Dist. of transmission (miles)
Pacific Light & Power Co.	150,000	50	59,500	1913	1	Δ	Y	D.	Δ	Δ	241
Au Sable Elec. Co.	140,000	60	19,000	1912	1	Δ	Δ	No	Δ	Δ	245
Southern Sierras Power Co.	140,000	60	8,750		1	Δ	Y	R	Δ	Y	239
Utah Power & Light Co.	130,000	60	42,000	1914	1	Δ	Δ	No	Δ	Δ	135
Pacific Gas & Electric Co.	125,000 to 110,000	60	25,000	1913	1	Δ	Y	D	Δ	Y	110
Tennessee Power Co.	120,000	60	15,000	1914	3	Δ	Δ	No.	Δ	Δ	140
Connecticut River Transmission Co.	120,000	60	14,400	1914	3	Δ	Y	D.	Δ	Y	60
Inawashiro Hydro-Electric Power Co.	115,000	50	42,000	1914	1	Δ	Δ	No	Δ	Δ	144
Grand Rapids Muskegon Power Co.	110,000	30	9,000	1906	1	Δ	Δ	No	Δ	Δ	35
Ontario Hydro-Electric Commission	110,000	25	106,800	1910	1	Δ	Y	R.	Δ	Y	90
Lauchhammer A. G.	110,000	50	15,000	1911	3	Y	Y	No	Y	Y	35
Georgia Ry. & Power Co.	110,000	60	50,000	1912	1	Δ	Y	R.	Δ	Δ	210
Alabama Interstate Power Co.	110,000	60	48,000	1913	1	Δ	Y	R.	Δ	Y	150
Mississippi River Power Co.	110,000	25	112,500	1913	3	Δ	Y	D.	Δ	Δ	144
Mexican Northern Power Co.	110,000	60	26,000	1914	1	Δ	Y	R.	Δ	Y	157
Lehigh Coal & Nav. Co.	110,000	25	30,000	1914	1	Δ	Y	R.	Δ	Δ	124
Ebro Irrigation & Power Co., Ltd.	110,000	50	50,000	1914	1	Δ	Δ	No	Y	Δ	105
Chile Exploration Co.	110,000	50	40,000		3	Y	Y	No	Y	Y	86
Sierra-San Francisco Power Co.	104,000	60	34,000	1910	1	Δ	Y	D.	Δ	Y	138
Yadkin River Power Co.	100,000	60	24,000	1912	3	Δ	Y	D.	Δ	Δ	96
Great Falls Water Power & Townsite Co.	102,000	60	21,000	1910	1	Δ	Δ	No	Δ	Δ	150
Central Colorado Power Co.	100,000	60	10,000	1909	1	Δ	Δ	No	Δ	Δ	152
Great Western Power Co.	100,000	60	50,000	1909	3	Δ	Δ	No	Δ	Δ	154
Southern Power Co.	100,000	60	75,000	1909	1	Δ	Y	R.	Δ	Δ	210
Shawinigan Water & Power Co.	100,000	60	45,000	1911	3	Δ	Y	R.	Δ	Δ	87
Los Angeles Aqueduct	100,000	50	22,500	1914	1	Δ	Y	D.	Δ	Y	47
Tata Hydroelectric Co.	100,000	50	40,000	1914	1	Δ	Δ	No	Δ	Δ	43
Appalachian Power Co.	88,000	60	20,610	1912	3	Δ	Δ	No	Δ	Δ	75
Rio Janeiro Tramway, Light & Power Co.	89,000	50	48,800	1913	1	Δ	Δ	No	Δ	Δ	51
Sao Paulo Elec. Co.	88,000	60	30,000	1914	1	Δ	Δ	No	Y	Δ	56
Mexican Light & Power Co.	85,000	50	58,500	1910	1	Δ	Y	D.	Δ	Y	169
Victoria Falls & Transvaal Power Co.	84,000	50	40,667	1913	3	Δ	Y	R.	Y	Δ	30
Toronto Power Co.	85,000	25	80,000	1914	1	Δ	Δ	No	Δ	Δ	80
Katsura Gawa Denryoku Kabushiki Kaisha	77,000	50	22,400	1912	1	Δ	Y	R.	Δ	Y	48
Southern California Edison Co.	75,000	50	20,000	1907	1	Δ	Y	D.	Δ	Y	117
Hidro-Electrica Espanola Molinar	70,000	50	22,500	1910	3	Y	Y	No	Y	Y	158
Pennsylvania Water & Power Co.	70,000	25	71,500	1910	3	Δ	Y	R.	Y	Δ	40

have been in operation for a considerable length of time, it seems somewhat superfluous to bring up arguments in support of this method of connecting transformers. Following is a list of power transmissions using transformers star-connected on the high-tension side which have been in operation for a considerable length of time.

Ontario Power Company	66,000	volts.
Southern Power Co	100 000	"
Ontario Hydroelectric Power Company	110,000	"

The table on p. 765 gives a list of power companies transmitting at 70,000 volts and above; 22 out of 37 of these use transformers which are star-connected on the high-tension side. One of the most recent is the large power development of the Mississippi River Power Co., the Keokuk development transmitting power at 110,000 volts. Perhaps the most notable of recent power developments is that of the Pacific Light and Power Company, transmitting at 150,000 volts, which employs the delta-star connection.

It will be evident from this table that the advantages of the delta-star connection are recognized by a large number of engineers; but it should be used universally for transmission voltages above 66,000 volts instead of in a little more than 50 per cent of the cases as the table indicates.

Conclusions

For transmission voltages below 44,000 volts, either transformers with star or delta-connected high-tension windings may be used; the delta connection has a slight advantage due to its greater flexibility. For transmission voltages above 44,000 volts, transformers with star-connected high-tension windings should be used.

This conclusion is upheld by sound reason and also because it has been tried out successfully on some of the largest transmissions in the world, several of which have been operating successfully for a number of years.

Presented at the 296th Meeting of the American Institute of Electrical Engineers, Pittsfield, Mass., May 29, 1914.

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EXPERIENCE OF THE PACIFIC GAS AND ELECTRIC CO. WITH THE GROUNDED NEUTRAL

BY J. P. JOLLYMAN, P. M. DOWNING AND F. G. BAUM

ABSTRACT OF PAPER

The paper gives an outline of the distributing system of the Pacific Gas and Electric Company of California which operates at 60 kv., the transformers being Y-connected, with the neutrals solidly grounded. The company considers the grounded neutral system has a number of important advantages with regard to the transformers, the transmission lines, and operation.

The fewer turns of larger capacity of the Y-connected transformers and the fixed lower average voltage to ground greatly increase their reliability.

The maximum voltage on the line insulators with the grounded neutral is never more than 57.7 per cent of the line voltage, and it is possible to maintain polyphase service at a substation on a branch line with only two wires in case one wire should be cut out. This cannot be done on a delta system unless one phase of the system be grounded, which is very undesirable.

With a grounded neutral, a wire down is instantly detected and power must be shut off. In a delta-connected system an arcing ground is often followed by surges which break down the insulation at other points, the cause of this disturbance being the oscillatory character of the arc. In the grounded Y system no such disturbances occur, as the frequency of an arc to ground is the same as that of the system and any damage is confined to the point of failure.

It is also believed that operation with the grounded neutral causes less disturbance in telephone and telegraph lines than would be the case in delta-connected lines.

THE PACIFIC Gas and Electric Company operates a very extensive 60-cycle transmission network in Central California. The 60-kv. system comprises about 1260 miles (2027 km.) of three-phase circuit. It is supplied directly by nine hydroelectric plants having an installed generator capacity of 67,310 kw. and three steam plants having an installed turbo-generator capacity of 68,000 kw. In addition there are 14,300 kw. of steam engine-driven generators in the company's steam plants which are held in reserve. The 100-kv. system which has just been put into operation has one hydroelectric generating station of 25,000 kw. capacity and 109.5 miles (176 km.) of circuit. The entire output is fed into the 60-kv. system through one substation.

For the purpose of the receipt or delivery of power the 60-kv. system is connected as follows: at Chico to the 60-kv. system of the Northern California Power Company; at Santa Rosa with the 60-kv. system of the Snow Mountain Water and Power Company; at a point near Folsom with the 60-kv. system of the Western States Gas and Electric Company; and at Oakland, through transformers, with the 100-kv. system of the Great Western Power Company.

These connections very considerably increase the length of circuit and total generator capacity connected to the 60-kv. system. The entire 60-kv. and the 100-kv. systems are usually operated in parallel.

The transformers at all the company's own generating stations and at all important substations have their high-tension windings Y-connected with the neutral solidly grounded. The low-tension windings of the generating station transformers are nearly all delta-connected as are also about half of the substation transformers. The remaining substation transformers have both windings Y-connected with solidly grounded neutrals. In most of the substations where the low-tension windings are delta-connected, a switch is provided between the high-tension neutral and the ground, which is normally kept open. This avoids the short-circuiting of one transformer in case of a ground on the transmission system and prevents the substation being cut off from the system by the opening of the protective devices on the high-tension side of the transformers. There are over 225,000 kw. of 60-kv. transformer capacity in the company's own generating plants and substations.

The Northern California Power Company, the Snow Mountain Water and Power Company and the Western States Gas and Electric Company operate their transformers Y-connected with the neutrals solidly grounded. The connection with the Great Western Power Company is through transformers connected delta to delta. This method of connection is not theoretically correct where power is to be fed from the delta-connected transformers into the grounded Y system, because a ground on one wire of the line connecting the delta-connected source of supply with the grounded Y system will impress 173 per cent of normal voltage across the high-tension windings of two of the transformers in the grounded Y banks. The resulting disturbance in the low-tension circuits is very severe. Our experience proves conclusively that this method of connection is not desirable.

At all generating stations, and at all important junction points and substations, the 60-kv. lines are controlled by oil switches. The lines are switched out under any condition of load or short circuit as occasion demands. The lines are also switched on at full voltage. We have operated in this manner for over 10 years and have never had any failures of transformers or of line insulation which could be attributed to this method of operation.

We consider that the grounded-neutral system as compared with the delta system affords the following important advantages:

1. *With Regard to Transformers*: Transformers are wound for only 57.7 per cent of the voltage required in the delta system. The average voltage to the neutral from all points of the windings is 50 per cent of the voltage from line to neutral; that of a delta bank is 69 per cent. The product of the turns times the average voltage to neutral in the Y-connected bank is 41.8 per cent of that in the delta-connected bank. The windings have 173 per cent the current capacity of the windings of a delta transformer.

In addition there is only one line terminal per single-phase transformer, wiring for a spare unit is much simpler and the high-tension windings may be used as auto-transformers in supplying small amounts of power to lower-voltage circuits.

The connection between the Pacific Gas and Electric Company's 100-kv. system and the 60-kv. system is made with auto-transformers connected grounded Y. We believe this to be the simplest, most reliable and most efficient connection that can be made between two such systems.

Our transformers have given so little trouble that we have not had much occasion to try to maintain service with only two transformers. We have had no difficulty, however, in carrying loads up to 2000 or 3000 kw. with two transformers.

Our experience confirms our belief that the fewer turns of greater current capacity and the fixed lower average voltage to ground of the transformers greatly increase their reliability.

2. *With Regard to Transmission Lines:* The maximum voltage on the line insulators is fixed and is never more than 57.7 per cent of the line voltage. Ten years ago the pin type insulator was the only type obtainable and the low fixed maximum voltage of the grounded neutral system has unquestionably been of great assistance in securing the best service from this type of insulator.

It is possible to maintain polyphase service at a substation on a branch line with only two wires in the event one wire should be cut out. This cannot be done on a delta system unless one

phase of the whole system be grounded, and this is very undesirable.

3. *With Regard to Operation:* With the neutral grounded, a wire down is instantly detected and power must be immediately cut off. This is exceedingly important where many of the circuits run through thickly settled districts. Inasmuch as practically all our important loads are reached by two lines or are on a loop, service is not more than momentarily interrupted by a failure at one point.

A line of any length may be charged at full voltage without shifting the static neutral. It is impossible to close all phases of a circuit at exactly the same instant. In a delta system the first phase closed will increase the capacity to ground of that phase of the system and thereby draw the static neutral toward that phase. The second phase acts in a similar manner and the static neutral does not return to the center of the delta until the three phases are closed. This sudden shifting of the static neutral is the cause of an unnecessary strain on the insulation of the system. We know of failures from this cause on delta-connected systems.

Finally, and most important of all, is the fact that in extensive high-voltage delta-connected systems a ground is often followed by a disturbance of such power that breakdowns of insulation at other points take place. Such a disturbance generally results in serious damage to apparatus and service. The cause of this type of disturbance is found in the oscillatory character of the arc which takes place from a delta-connected system to ground, together with a large amount of current which will flow in such an arc if the system is extensive. In the event of a ground on a delta-connected system, the charging current, which is a function of the voltage from wire to neutral, will be increased because the neutral is shifted from the center of the delta to one corner. This increase will be about 73 per cent. The current flowing in the arc to ground may be nearly equal to the increased charging current, and this on our 60-kv. system would amount to about 400 amperes. The circuit containing the arc, line reactance and capacity from line to ground tends to oscillate. Such an oscillating arc is very likely to set up disturbances of high power, especially when there is any such current as 400 amperes involved. We have seen evidence that such a disturbance may cause high voltage to ground on the wire on which there is an arcing ground. This fact would probably cause the operation of an arcing ground suppressor to be very unreliable.

Certain districts in which we operate occasionally have heavy fogs which are carried in from the Pacific Ocean by the prevailing westerly winds. It has been our experience in these districts that lines on pin insulators have given better service when operated grounded Y at 60 kv. than when operated delta-connected for a much lower line voltage. It seems probable that the leakage over the insulators in foggy weather was sufficient to set up oscillatory disturbances which caused more trouble than has the higher but more stable line voltage.

We have found that the grounded Y system is entirely free from such disturbances as these. The frequency of an arc to ground is that of the system. Any damage is confined entirely to the point of failure. The short-circuit currents have not caused any damage to generator or transformer windings. Due to the distribution of the sources of power, any given point on the system will have a good many miles of line between it and several of the generating plants. Hence it is doubtful in many cases if more current would flow in a short circuit to ground than would flow to ground if the system were delta-connected. The drop over the lines from the more remote generating plants to a point at which a ground may take place, serves to prevent the voltage at points removed from the trouble from dropping to zero, and therefore the service is not seriously interfered with except in the vicinity of the trouble.

We believe that the operation of our system with the neutral grounded causes less disturbance in the circuits of our neighbors, the telephone and telegraph companies, than would be the case if we operated delta-connected.

Briefly, the induction in parallel telephone or telegraph circuits is caused principally by any unbalanced currents in the phases of the high-tension circuits, that is, currents returning through the ground, and by the presence of voltage to ground on the line conductors. The last cause is by far the most important, because the unbalanced currents during normal operation may be kept very small, while the voltage to ground is always high. A ground on the grounded-Y system will not cause much, if any, more current unbalanced than will a ground on a delta-connected system. The unbalanced current is at normal frequency on the grounded-Y system instead of at a very much higher frequency as is usual on the delta-connected system, hence the parallel circuits are not affected so unfavorably. It is our experience that even a considerable amount of unbalanced current at the normal 60-cycle frequency has little noticeable effect on

parallel telephone circuits. The unbalance will be immediately removed from the grounded-Y system in all cases, whereas a delta-connected system may occasionally be operated a short time with a ground before a final shut-down takes place. The definite limit on the voltage to ground is of very great advantage to the parallel circuit.

Conclusion

The operation of our high-tension network with the grounded neutral has been entirely satisfactory. We do not believe that we could give as good service, with as high a degree of safety to the public, with any other system.

DISCUSSION ON "INFLUENCE OF TRANSFORMER CONNECTIONS ON OPERATION" (BLUME), "A STUDY OF SOME THREE-PHASE SYSTEMS" (FORTESCUE), AND "EXPERIENCE OF THE PACIFIC GAS & ELECTRIC CO. WITH THE GROUNDED NEUTRAL" (JOLLYMAN, DOWNING AND BAUM), PITTSFIELD, MASS., MAY 29, 1914.

Guido Semenza (by letter): Italy is one of the countries of Europe which has largely developed the electric transmission of power from hydroelectric installations. In fact there are in Italy, the area of which is about double that of the State of New York, more than 2400 hydroelectric power houses, nearly all of them provided with transmission and distribution lines.

It may be of some interest to you to know the general opinion in this country on the problem under discussion.

The writer recently questioned the engineers of several Italian plants in order to have their opinion: The power of these plants varies from a few thousand kilowatts to 40,000 kw., with transmission by overhead lines at voltages varying from 6000 to 88,000 volts and by underground lines up to 25,000 volts.

First, concerning overhead high-tension transmission:

a. The great majority of the systems are delta-connected, consequently insulated from the ground.

b. A few are Y-connected with a spark gap (horn-arrester) between the neutral points and the ground.

c. A few have a real grounded neutral point across a resistance of some kind.

d. Only two to my knowledge have the neutral point grounded without resistance, (which I will call a short ground).

Second. Concerning underground high-tension lines: No system of this kind is known with grounded neutral, either with or without resistances.

Third. Concerning low-tension distributions: All sorts of arrangements are to be found, insulated delta, grounded Y, four-wire three-phase with grounded neutral, etc.

It must be noted that the first three-phase transmission plants constructed in Italy were planned with delta insulated connection, and their operation having proved satisfactory from the beginning, the same arrangement has been generally adopted all over the country.

Only later, in some installations in which a number of disturbances were noticed, as a trial, the neutral was grounded both in the power house and at some extreme point of the distribution; in some cases the practise proved to be good, as some of the disturbances were eliminated, while in other instances the remedy had a contrary effect.

For instance, on the Subiaco-Roma line, where current is generated directly by alternators at 33,000 volts, the maker of the alternators imposed a grounded neutral; but the moment an insulator was punctured the gradient of tension was so steep that it was

dangerous to walk about in the power house, the current passing through the ground not being always sufficient to trip the circuit-breaker.

In a general way, very serious disturbances were caused in telephone and telegraph circuits.

Among the large systems, only that of the Societa Conti per Imprese Elettriche has a short-grounded neutral of 50,000- and 25,000-volt overhead lines. This is one of the systems which is improved with the grounding; but a long period of disturbances on telephone lines was experienced. At last it was found that the principal cause of these was the third harmonic, due to oversaturated transformer.

The plant of the Municipality of Milan at 60,000 volts has the neutral point grounded through a water jet discharger.

The operation is good, but on both these systems interruptions of service are more frequent when compared with other analogous plants delta-connected.

Nearly all the other large systems are delta-connected, thus insulated from the ground. I recall the Milan Edison Company (15,000 volts), the Societa del Cellina (30,000 volts), the Societa Adamello (72,000 volts), the Societa Meridonale di Elettricita (88,000 volts), the Societa Dinamo (50,000 volts), the Societa Imprese Elettriche Roma (60,000 volts), and many others.

Being personally in favor of the insulated delta arrangement, I will summarize here the reasons which are generally given in favor of this solution in my country:

1. With good circuit-breakers, a ground on line will always result in an interruption of the line. Although keeping a a line in service, with a ground on it, is not very frequent, it has sometimes occurred without giving any trouble.

2. The grounding through a resistance is an immediate solution which presents the disadvantages of both insulated and grounded systems. In fact, the disadvantage of the insulated system is said to be that full delta tension is put on an insulator when a line is grounded; but the resistance, grounded neutral, when the accidental ground has a low resistance, so that the current is high, can give such a drop on a neutral connection that the tension on the insulators may rise quite near to the full delta value.

3. Ground connection is never a sure device. Moreover, a ground is effective only locally, but not at any distance. Therefore, only one ground in a large system is not considered sufficient.

4. Short-grounded neutrals are apt to disturb all low-current circuits. (Telegraph, telephone, signaling).

5. The practise in Italy is to over-insulate lines. It is considered that money spent in using larger insulators is well spent. So the advantage of grounded neutral in cheapening the cost of lines is not of great value here.

6. One of the most serious disturbances on long-distance transmissions is the traveling surges caused by atmospheric

influence. It is not yet demonstrated that the grounded neutral has any beneficial influence on the accidents caused by such disturbances.

7. It is said that a neutral grounded prevents the accumulation of static charges. In many Italian systems this accumulation is prevented by water jet dischargers, acting on the busbars or on the line wires.

Concluding, I do not see many reasons for supporting the grounding of a neutral point, while I see many advantages in not doing it. I am persuaded that by using good insulation and good terminal protection, the insulated system affords all conditions for good and regular operation.

F. F. Brand: With reference to one of the points Mr. Semenza mentions, that is, that with the grounded Y connections, serious disturbance was found to occur in telephone and telegraph lines, I would state that this disturbance can be considered to be due to two causes—one is current and one is voltage interference. Current interference can only occur where the current flowing in the lines is in the same direction in all the lines at the same instant, that is to say, there must be a current returning through the earth. In order to get a return current through the earth, it is necessary that there should be unbalanced currents in the line, or a triple-harmonic current flowing through the earth.

In Europe it is common practise to use Y-Y-connected transformers. If the transformers are shell-type construction, there will be a triple-harmonic current flowing in the lines and a triple-harmonic return current flowing through the neutral, at the same instant, but if these machines are three-phase core-type there will be no appreciable flow of current to the neutral, due to the fact that there is practically no triple-harmonic voltage between line and neutral in the core type transformer.

With reference to the interference with telephone lines, and other voltage disturbance, there can be no great difference in the Y and delta connections.

W. W. Lewis: There are in North America, according to a statement issued recently by the *Electrical World*, (issue of April 25, 1914), 35 transmission systems operating at 70,000 volts and over, and in the remainder of the world 19 such systems. The following tabulation shows the division of these systems into Y and delta:

	Y	Delta	Not given	Total	Grounded neutral
North America	19	14	2	35	18
Remainder of the world	10	6	3	19	6
	29	20	5	54	24

From the above it will be seen that of the forty-nine systems on which data are given, 29, or about 60 per cent, are Y connected, and 24, or about 50 per cent, have grounded neutral.

In North America, however, practically all the Y-connected systems are grounded, and about 55 per cent of the total number of systems.

These figures show a remarkably close division of opinion among operating engineers as to the relative merits of grounded Y and isolated delta, with the preponderance slightly in favor of the grounded Y in North America, at least. The following tabulation shows the number of systems started up each year, beginning with 1901, when the first one was put into operation:

Year	Number
1901	1
1906	2
1907	1
1908	0
1909	3
1910	8
1911	5
1912	6
1913	7
1914	13
1915	5
	51
Not given	3
	54

It will be noted that only four of these systems were installed prior to 1909. Counting the years 1914 and 1915, when some of the systems will be put into operation, practically the total development of high-tension transmission has taken place in about seven years. It is small wonder, then, that opinion should be divided as to the best method of connection, and that practical operating men are solving the problem by the method of experiment, which is after all the only conclusive method.

In the present discussion the writer has selected a half-dozen typical systems, three of which are connected isolated-delta and three grounded Y, and will briefly discuss certain points in their operating experience.

First. Great Western Power Company. (Isolated Delta).

This system is the only one of importance operating isolated delta in the State of California. It runs from Big Bend to Oakland, and is about 154 miles long. At no point is the altitude over 500 feet.

The operating voltage is 100,000 volts. Operation was begun in 1909. There are two circuits on the same towers, the conductors being arranged vertically. There is one overhead ground wire at the middle of the towers.

Lightning is very infrequent (about twice a year) and no

trouble is caused by it. Short-circuits and arcing grounds cause some trouble (about once in two or three months). Arcing grounds destroy the telephone communication, break down insulators, and frequently burn off the line wire. Short circuits also necessitate shutting down the system.

At Oakland, the Great Western system is connected by delta-delta transformers to the grounded-Y system of the Pacific Gas & Electric Company. Some of the disturbances originating on the latter system, no doubt, are felt on the former system.

Second. Colorado Power Company. (Isolated Delta).

This system consists of two parts, the Shoshone-Denver line, one hundred and fifty-three miles long, and the Boulder-Denver line, twenty-eight miles long. The two lines are capable of being tied together at the Denver substation. The operating voltage is 100,000 volts. The system has been in operation since 1909. The transformers at all points are delta-connected on the high side, except at Boulder, where they are isolated-Y. The conductors are placed horizontally. There is one ground wire at the middle of the towers.

The Shoshone-Denver line runs over some of the roughest country in the United States, and at one place reaches an altitude of 13,500 feet. Lightning is severe at certain times of the year, and wind velocities of 150 miles per hour are at times recorded.

An analysis of the disturbances of this system in 1912 shows 42 per cent due to wind, 30 per cent due to lightning, and the balance due to construction failures, extraordinary causes and unknown causes.

The greatest part of the trouble is due to short circuits, caused by wires swinging together during wind storms, and by arcing grounds, due to the lines swinging against the towers or ground wire. A shut-down usually results from either a short circuit or an arcing ground.

It has been found impossible to operate the long Shoshone-Denver line with one conductor dead grounded, due to the increase in corona loss and charging current.

The short Boulder-Denver line, however, has been operated for hours with a dead ground on one line.

However, a ground on the line, either arcing or dead, interferes with telephone communication, and this usually necessitates a shut-down.

Third. Au Sable Electric Company. (Isolated Delta).

The main line of this system operates at 140,000 volts, and extends from Au Sable to Owosso, in eastern Michigan, a distance of about 160 miles. The system consists of a single circuit, the conductors being arranged two on one side and one on the other side of the tower. There is no ground wire. Operation was begun in 1912.

The lightning is very severe. The country is open and the lines are much exposed. Practically all the storms which cause interruption of service occur during the season from May to

September. Lightning causes simultaneous arc-overs from two or three lines to ground over insulators or bushings, thus resulting in phase short circuits.

Fourth. Sierra & San Francisco Power Co. (Grounded Y):

This system is located in California, in much the same kind of territory as the Great Western Power Company system. The line extends from Stanislaus to San Francisco, a distance of about 135 miles. The operating voltage is 104,000, the maximum altitude about 1000 feet. Operation was begun in 1910. The system consists of two circuits on the same towers, conductors arranged vertically, no ground wire. The two lines are connected in parallel on the low-voltage side. The neutrals on both ends of the line are dead grounded.

Short circuits by leaky insulators, large birds, etc., occur on an average of about once a month.

Short circuits are usually taken care of by separating the lines on the low-voltage side and cutting out the affected line. Grounds rarely develop into short circuits between phases, but the line wire or the insulators usually burn off. There is practically no lightning trouble on this system.

Fifth. Yadkin River Power Co. (Grounded Y).

This system is situated in North Carolina, and the main line runs from Blewett's Falls to Method, a distance of about 90 miles. The operating voltage is about 100,000 volts.

There are two circuits on steel towers, the conductors in a vertical plane, one ground wire at the middle of the towers. The neutral is dead grounded at the generating end only.

Lightning is extremely severe for several months in the year. Operation of the system was commenced in 1912, with isolated neutral; but this was changed after about a year to grounded neutral.

Grounds and short circuits are frequent. A device has been used to reduce trouble from short circuits. This consists of a relay in the neutral, which, when operated by ground current, throws a large resistance in series with the field of the generator exciter, thus momentarily reducing the voltage and allowing the short circuit to die out.

Sixth. Pennsylvania Water & Power Co. (Grounded Y).

This system is grounded through a resistance. The power is generated on the Susquehanna River, in southern Pennsylvania, and transmitted at 70,000 volts to Baltimore, a distance of about 40 miles. There are two sets of towers, with two circuits per tower; conductors arranged vertically; one ground wire per tower. Operation was begun in 1910.

The lightning is severe in this district and short-circuits due to insulators flashing over are frequent. Interruptions have been greatly reduced by a device which short-circuits the line at the station through a fuse, thus allowing the arc over the insulator to become extinguished. This device is supplemented by another consisting of series line relays, which act on the

generator field, opening it momentarily and then closing it, the whole action taking place so rapidly that synchronous apparatus does not get out of step. With the assistance of these auxiliary devices, operation is said to be very satisfactory.

Conclusions. It will be seen from the above that neither the isolated-delta nor grounded Y systems are free from trouble.

The amount of trouble is governed largely by location, climate and mechanical details of line construction.

Two arguments which are frequently used in favor of the isolated-delta system are proved in practise to be fallacious:

First, that only voltage troubles need be expected. On the Colorado and Au Sable systems phase short-circuits are numerous.

Second. That a delta system can operate continuously in case of a dead ground on one line. This is only true for very short lines, as on long lines the charging current—due to the increased capacity and voltage—becomes excessive, likewise the corona loss. The telephone system is also invariably disturbed, so on this account operation usually must be discontinued.

On the other hand, the short-circuit troubles on the grounded Y system are very severe, and some auxiliary short-circuiting and field-destroying devices are almost essential to render satisfactory operation.

As far as operation is concerned, it seems that both systems have their advantages and defects, and that in selecting a system, the location and climatic conditions should be carefully considered.

V. M. Montsinger: About a year and a half ago, Dr. Steinmetz and Mr. Faccioli suggested to Mr. Blume and myself an investigation of the effect of electrostatic capacity and reactance on third harmonics in Y auto-transformers.

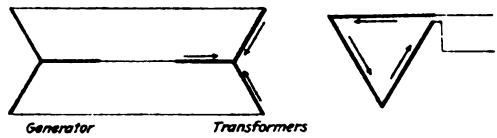

FIG. 1—DIAGRAMMATIC SKETCH OF GENERATOR AND TRANSFORMERS FOR MAKING THIRD-HARMONIC VOLTAGE TESTS. ARROWS SHOW DIRECTION OF TRIPLE-FREQUENCY VOLTS.

Some tests were made on small transformers connected as shown in Fig. 1 to determine to what extent the triple voltage was increased by electrostatic capacity supplied from condensers connected across the legs of the secondary windings. The transformers were excited from a Y-connected generator of several times the sum of the capacities of the transformers.

A rather peculiar phenomenon was found to take place, that

is, when the condensers were connected, the triple voltage, at a certain value of the core density, suddenly rose, almost in a straight line, to a value slightly over 200 per cent of the fundamental; but on increasing the core density, the triple voltage decreased almost as suddenly to approximately its normal value, corresponding to that particular density without capacity. This same phenomenon occurred also when the condensers were placed across the opening in the delta.

By connecting the transformers as shown in Fig. 1, we were able to differentiate the triple voltage from the fundamental and other higher harmonics, not multiples of the third, and to

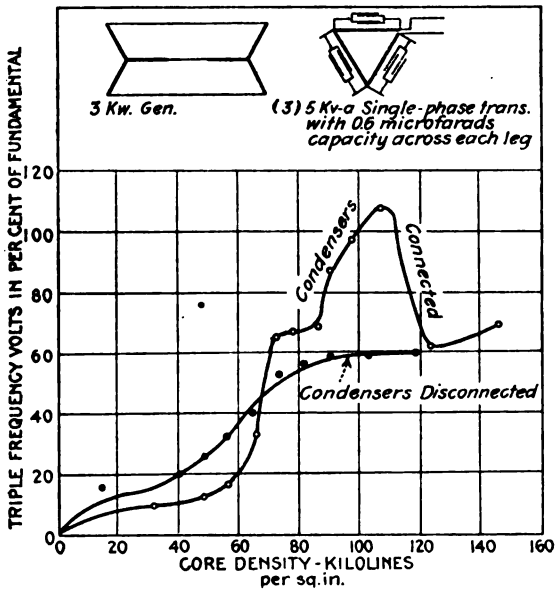

FIG. 2—CURVES SHOWING TRIPLE-FREQUENCY VOLTS OBSERVED ACROSS OPEN DELTA, WITH AND WITHOUT CONDENSERS CONNECTED ACROSS DELTA LEGS

determine the third harmonics in per cent of the fundamental voltage.

Fig. 2 shows the results of tests recently conducted with three 5-kv-a. core-type transformers connected with and without condensers, and excited by a 3 kw. generator as shown by the sketch in the upper part of the diagram.

Fig. 3 shows the same transformers and generator connections. The condensers in this case, however, were connected in an opening in one corner of the delta, and the voltage read across the condensers. In this case, as will be seen later, the condensers draw only a triple-frequency current.

For the case as given in Fig. 2, the condensers draw a complex current which is composed of the fundamental and of the triple frequency. The same condition would be true if the condensers were connected between the neutral point to the lines of the Y on the excited side of the transformer, which case represents the conditions existing with a transmission line of an isolated system connected to Y auto-transformers with the neutral point grounded.

The indications are that if we have the right conditions existing, that is, if the electrostatic capacity of a transmission line is of the proper value, and if the flux density of the transformers

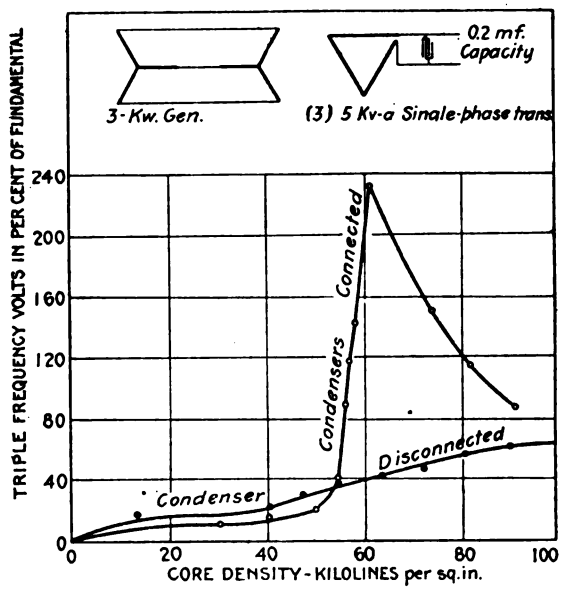

FIG. 3—CURVES SHOWING TRIPLE-FREQUENCY VOLTS OBSERVED ACROSS OPEN DELTA, WITH AND WITHOUT CONDENSERS CONNECTED

is at the point to allow third-harmonic intensification, there may be severe line disturbances which would cause strains on the line and transformer insulation.

With these transformers, excited by the small generator, as shown in Figs. 2 and 3, an increase or a decrease in the electrostatic capacity gave a smaller intensification, or peak value, of the triple-frequency volts, while with the larger generator, with practically the same transformers, the indications were that with a larger condenser capacity, the peak values would have been still larger, but on account of the condensers being of low voltage, and arcing over, higher values could not be recorded. However, since the iron in transformers is generally worked

The results of tests made with three single-phase transformers operating at a flux density of 97 kilolines per sq. in., are shown in Fig. 7. The conditions were perfectly balanced, but the disadvantages found were: first, that the transformer efficiency was comparatively low; second, that the power factor was very poor, and third, that there was practically no voltage regulation whatever. The maximum efficiency of output divided by input was about 80 per cent, while that of the output divided by the transformer rating was only about 17 per cent. The maximum power factor was about 0.27. However, Mr. Taylor, an English engineer,* proposes a means of improving the regulation although the efficiency and power factor are still low.

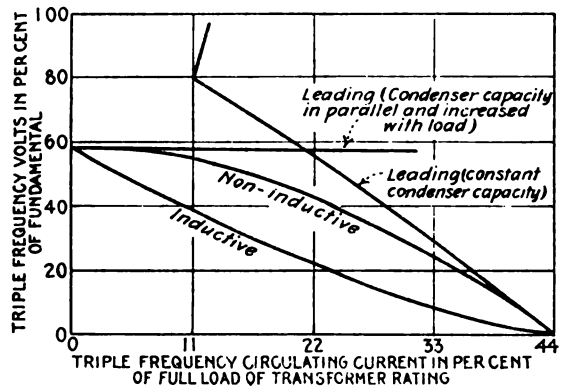

FIG. 7—CURVES SHOWING VOLTAGE REGULATION FOR LEADING, LAGGING AND NON-INDUCTIVE LOADS ACROSS OPEN DELTA OF THREE 5-KV-A. SINGLE-PHASE Y-DELTA-CONNECTED TRANSFORMERS, OPERATING AT A CORE DENSITY OF 97 KILOLINES

The following illustrations show the shapes of the current and voltage waves at different points on these curves.

Fig. 8 was taken at a density of 65 kilolines, and shows the waves of the voltage across the opening in the delta and across the lines of the Y side. No condensers were connected.

Fig. 9 shows the voltage across the leg of the delta and across the opening in the delta with condensers across the delta legs. Density 100 kilolines.

Figs. 10 and 11 show the voltage across the leg of the delta and amperes in the exciting lines. Densities 110 and 140 kilolines.

Fig. 12 shows voltage across the leg of the delta and amperes in exciting lines. Density 62 kilolines.

Fig. 13 shows voltage across the opening in the delta and across delta leg. Density 62 kilolines.

(In order to show these points of intensified triple frequency, there were set up in the hall the three 5-kv-a. trans-

*See London *Electrician*, May 8, 1914.

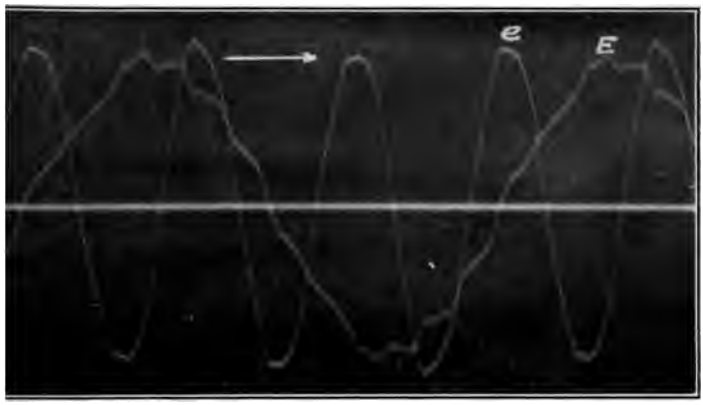

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FIG. 8

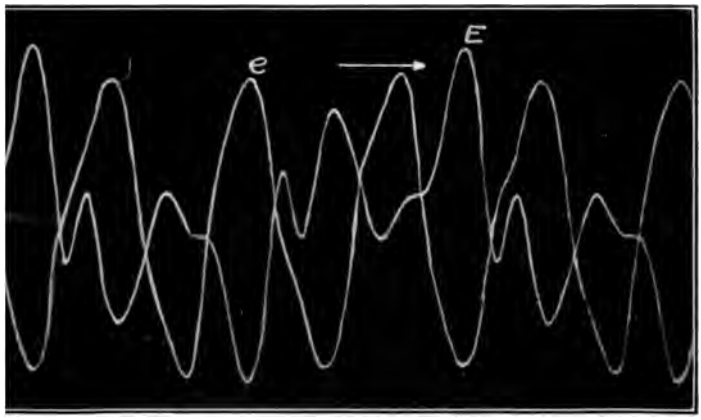

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FIG. 9

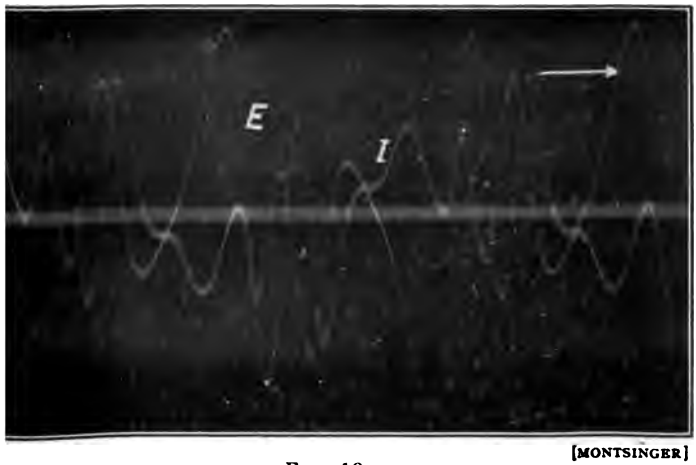

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FIG. 10

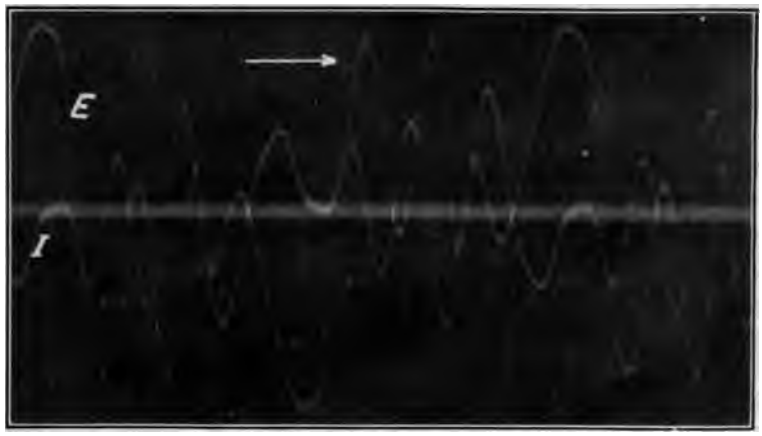

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FIG. 11

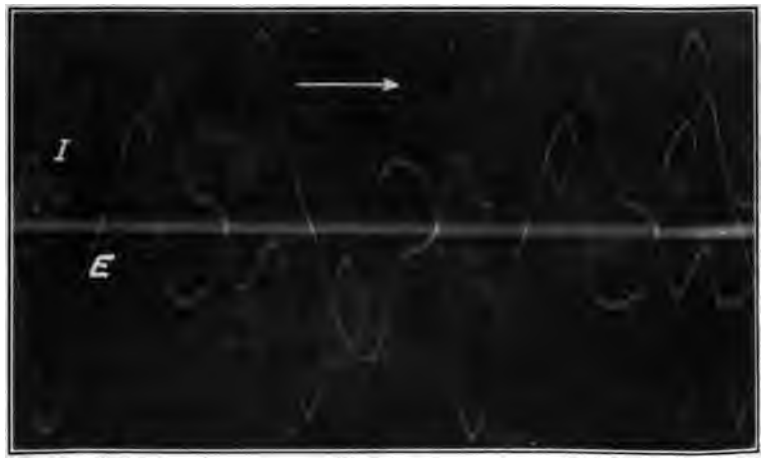

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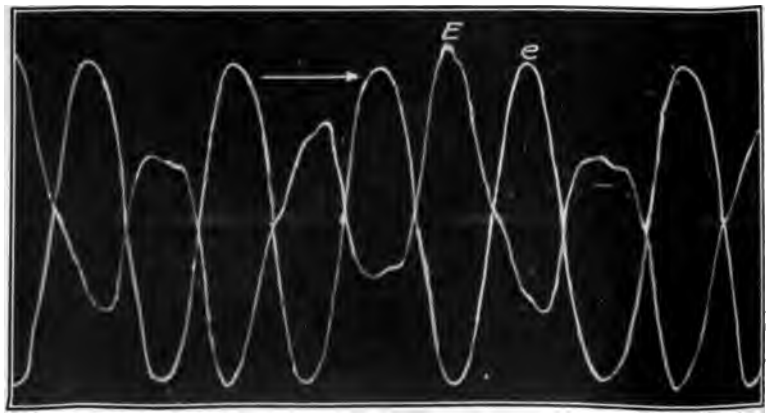
FIG. 12



[MONTSINGER]

FIG. 13

formers and the 3-kw. generator and motor used in obtaining these curves. It was arranged that the shadow of the needle of the voltmeter, reading the volts across the opening in the delta, was thrown on the screen as it moved. The variations of the triple-frequency volts, as the flux density was increased and decreased, were shown: first, without the condensers; second, with the condensers across the delta legs, and third, with the condensers across the opening in the delta).

C. M. Davis: Does the maximum point shift up or down as the different capacities are placed across the opening in the delta?

V. M. Montsinger: This is the maximum point that I could obtain with this apparatus. If I added more condensers, the point would be lower and if I added less condensers, it would be still lower.

C. M. Davis: Does resonance, or something like that, affect it?

V. M. Montsinger: I do not think that it is a case of resonance.

C. M. Davis: If it were resonance, you would get that high peak occurring at different flux densities, would you not?

V. M. Montsinger: In some cases it does begin to rise again if we go to a still higher density, but in this case, it does not rise again; but with the larger generator, it does.

C. M. Davis: My point is that if it is a case of resonance, inserting a different capacity across the opening of the delta would cause the maximum peak to occur at different flux densities. For instance, instead of the maximum peak occurring at about 60 kilolines, with another condenser, it might occur at 40 kilolines and with still another condenser, it might occur at 70 kilolines.

V. M. Montsinger: As pointed out before, and as was shown in Figs. 3 and 4, it occurs at different flux densities for different capacities across the opening in the delta; the greater the capacity, the lower the density at which the maximum peak takes place.

L. F. Blume: The particular density at which the peak will occur depends on the electrostatic capacity, and the condition of saturation of the iron. If more capacity had been inserted, the peak would have occurred at a lower density. The reason the amount of intensification increases as the density increases, is the fact that the iron is operated at a higher degree of saturation, making the third-harmonic charging current less effective in increasing the third-harmonic voltage. I think that the phenomenon is not one of resonance, because a critical value of electrostatic capacity and reactance is not required to obtain the result. It is more analogous to the rise in voltage which takes place in a generator when delivering a leading wattless load. The third harmonic can be considered as being generated in the windings of the transformer on account of the variable permeability of the iron, which, when connected to a leading wattless load, is increased thereby.

H. S. Osborne: Several references have been made to the inductive interference caused in telephone circuits by the operation of parallel high-tension power circuits. In the paper by Messrs. Jollyman, Downing and Baum, the view is expressed that their grounded star-connected system causes less disturbance in telephone circuits than it would if connected in any other way. It should be noted that this remark is evidently given as a statement of personal opinion and not as a conclusion which has been established.

Much trouble has been caused in telephone circuits by power circuits, both of the grounded star and of the delta-connected type. There are all over the country, particularly in the State of California, many telephone toll circuits, the serviceability of which is in large measure destroyed because of inductive interference from high-tension lines with grounded neutrals, under normal operating conditions. At times of abnormal conditions on power circuits, parallel telephone toll lines or telegraph lines are put out of service by the operation or the destruction of the protective apparatus, and sometimes by the destruction also of cables or of central office apparatus. It is doubtful whether a sufficient number of comparative observations have been made of the disturbance from delta-connected and from grounded star-connected power systems under conditions which are otherwise the same, to make possible a final conclusion regarding the relative severity of the electric disturbances from these two types of power circuit when both are so constructed and operated as to minimize the interference. Taking into consideration, however, the character of the disturbances, the experience of the telephone companies throughout the country would not incline them to support the authors' view, but rather the contrary conclusion.

An attempt has been made to compare the inherent features of delta and grounded-star connections in so far as their inductive effects are concerned. In comparing the relative inductive effects from different systems, it should be remembered that if the systems were perfectly balanced, that is, if the vector sum of the voltages between the line wires and ground were zero, and current in the ground were zero, the inductive effects from different three-phase systems would be similar. In considering the different systems, the comparison should, therefore, be made of the unbalanced components of voltage and current. A delta-star-connected system with the neutral point non-grounded would have an electrical balance similar to that of a delta-delta-connected non-grounded system. The comparison has, therefore, been made between the relative inductive effects due to the unbalances which occur in the delta-delta system and the delta-star system with grounded neutral.

This comparison is summarized in a table which is given below as a part of the record of this discussion. In brief, the comparison indicates that under abnormal conditions, either

the delta-delta or the delta-star grounded system will make entirely inoperative telephone circuits which are severely exposed to them. The relative magnitude of the inductive effects under these circumstances depends largely on conditions. Under conditions of normal operation with balanced loads, the unbalances in the delta system may be reduced to a minimum. The unbalances in the grounded system may be restricted to the third harmonic and its multiples, and these may be of relatively small magnitude. With unbalanced loads, the inductive balance of the delta system remains good, but the inductive effects from the grounded system become severe.

In view of this analysis and of the experience of the telephone companies, the presumption seems to be against the grounded system. It is believed, however, that no one is at present in a position to make an authoritative statement regarding the relative inductive effects inherent in grounded and non-grounded systems. As far as I am aware no thorough study has been made of the relative possibilities of reducing interference from these two types of systems. Unless adequate measures are taken to minimize the inductive effects, the disturbances from systems of either type may be very damaging, as the telephone companies can abundantly testify.

With the rapid increase in the networks both of telephone and high-tension power circuits, it is becoming increasingly difficult to keep the two classes of circuits adequately separated. It is, therefore, becoming more and more important that power circuits be constructed and operated in such a way as to minimize the disturbances which they cause in parallel telephone and telegraph circuits. If it should be found on thorough investigation that the inductive effects from grounded and non-grounded systems are substantially different in amount when each is provided with all the precautionary measures which are practicable and reasonable, then this consideration should be given its full weight in determining which type of transformer connection should be employed.

Comparison of Delta-Delta and Delta-Star Grounded Connections for Three-phase Power Transmission Circuits from the Point of View of Inductive Interference in Parallel Telephone and Telegraph Circuits.

Delta-Delta	*Delta-Star Grounded*
(a) Normal Condition of Power Circuit.	(a) Normal Condition of Power Circuit.
Balanced Loads:	*Balanced Loads*:
If line is well insulated, the voltages to ground are determined by the capacities between the ground and the line wires throughout their entire length and the capacities of all other	Voltages to ground balanced to somewhat higher degree than transformer windings. No fundamental current through neutral. Third harmonic magnetizing current and its multiples

lines in direct metallic connection to the line under consideration. Voltages to ground will be balanced provided entire system is so transposed as to equalize capacities between line wires and ground, and provided system is without leaks.

Under these conditions no current will flow in the ground except a very small charging current between adjacent transposed sections.

Unbalanced Loads:

Voltage unbalance to ground is caused by differences in impedance drop in the different phases. This effect small.

Currents in ground limited to unbalanced charging current. This effect small.

(b) Abnormal Condition of Operation.

One Wire Open:

Makes power system inoperative. Causes severely unbalanced voltages and severe interference in telephone circuits.

One Wire Grounded.

Not always discovered by power company. Voltages unbalanced throughout entire system with correspondingly severe disturbances in telephone systems. There is a danger of high-frequency oscillations due to an arcing ground, although there is no record of trouble experienced by the telephone companies which has been definitely traced to this specific cause. In a great many cases the voltage unbalance with one wire grounded without the occurrence of an arc is of itself sufficient to render parallel telephone circuits inoperative.

circulate in delta windings. A sufficient amount flows through neutral connection and ground to provide e.m.f. for circulating currents. Currents flowing in ground may therefore be small but may cause disturbance in telephone circuits because of exquisite sensitiveness of telephone apparatus to currents of frequencies of the third and higher harmonics of 60-cycle systems. These harmonics are not essential to the operation of the power system, and means can possibly be found to prevent their flow through ground.

Unbalanced Loads.

Voltage unbalance to ground is caused by differences in impedance drop in the different phases. This effect is small.

Current unbalance equivalent to difference in load currents flows through neutral and ground. A small current causes relatively very severe inductive effects because locus of current in ground is far below surface and because current contains harmonics in addition to fundamental.

(b) Abnormal Condition of Operation.

One Wire Open:

Not always immediately discovered by power company. The total load current carried by the two conductors which remain in service returns through ground. Disturbances in telephone circuits very severe.

One Wire Grounded:

Makes power system inoperative. Heavy current flowing through fault supplied from many lines in an inter-connected system gives very severe and widespread disturbances in parallel telephone circuits

F. E. Haskell: Is the inductive disturbance chiefly electrostatic or electromagnetic; that is, to what extent will each kind occur?

H. S. Osborne: The question is asked whether inductive disturbance is chiefly electrostatic or electromagnetic. The relative importance of these two effects depends very largely indeed on the conditions of individual cases. Note should be made, however, of a marked difference in the ease with which the zone of serious electrostatic and electromagnetic effects can be limited.

The presence near the power wires of conducting or partially conducting bodies, such as overhead grounded wires or the earth, is much more effective in restricting the electrostatic field than in limiting the electromagnetic field. This difference arises partly from the fact that relatively small charging currents are sufficient to largely influence the electrostatic field and relatively large circulating currents are necessary to considerably limit the electromagnetic field. Unbalanced current from the power circuit flowing in the ground does not behave as though the ground were a perfect conductor, but distributes itself very widely and causes correspondingly widespread inductive effects. Generally, telephone and telegraph circuits have not been subjected to severe electrostatic disturbances, provided they are more than 200 or 300 ft. away from the disturbing circuit. Severe electromagnetic disturbances have, however, been experienced at considerably greater distances from the power circuits. An extreme case of electromagnetic induction is represented by the New Haven Railroad, which caused serious electromagnetic induction in telephone circuits about five miles from the disturbing circuits.

C. O. Mailloux: There is one point the speaker might have emphasized. The effects from electrostatic action are due to the combined effects of the line, whereas the electromagnetic effects are due to current passing through the line. That was clearly shown in the case of the very high potential transmission system in Michigan, a system employing over 140,000 volts, where the electrostatic induction in a telephone line situated at considerable distance from the power line was quite marked. That is clear from the fact that we know that electrostatic induction depends upon the potential of the line, whereas electromagnetic induction depends upon the magnetic field, which is itself a function of the current flowing through the line. The matter is of great interest, and I hope there will be discussion on it.

E. E. F. Creighton: In regard to the relative value of electrostatic and electromagnetic induction effects, it seems to me the electromagnetic effect from power circuits is and always will be a greater menace to telephone lines and any other parallel lines. The electrostatic can be taken care of in many ways that are practicable, but the electromagnetic seems to use such a depth of the earth, and forms such a large loop in conjunction

with the telephone line, that it makes it impossible to screen it in any way.

Some tests were made some time ago where the distance between the lines was 30 feet—they were on opposite sides of the roadway. The power line was grounded at the further end and the current was returned through the earth where there were salt marshes and consequently where one would expect the current to flow through the highly conducting surface. The values of induction between these two circuits were measured and from these measurements calculations were made of the equivalent loop of the primary and secondary, considering them simply as a transformer with one turn on the primary and one on the secondary. The equivalent loop gave a depth to the center of the current in the earth of 260 feet below the surface, consequently, although the wires were only 30 feet above the surface, one must consider the equivalent return circuit as at a great depth, and the possibility of screening the electromagnetic induction between these large loops of circuit seems almost hopeless.

John B. Taylor: It is a source of considerable gratification to me to see the trend of these papers on the matter of transformer connections Y versus delta, because, while I am not prepared to say I always favor the Y connection, I have had occasion in past years to recommend Y connections when I found myself in a minority. Just now it looks as though the pendulum is swinging the other way, and it may be well to put in a word of caution lest the pendulum swing too far.

This question of Y and delta connection is not ever to be settled by argument, or ever to be finally settled, because both arrangements have advantages, and the conditions under which they are used have been and will be variable, so that for a given system the advantages might lie with one connection or the other, in the future the same as they have in the past.

I would like to say that there is always a lot of confusion in discussing this point, which confusion has not been altogether absent in this discussion this morning; in other words, Y connection does not inherently mean grounded neutral. You can keep just as clear from the grounded neutral with the Y connection as you can with delta connection, so if you prefer to build your transformers with one or both parts connected in star, because of safe requirements, do not let the bugaboo of the currents in the earth keep you from doing it. There may be an advantage in tying to the earth at one or more points, but if it seem desirable to keep clear of the earth, that need not be the controlling factor in the connection of the transformer. This point always seems to be in evidence in a discussion of this subject and accounts for much of the discussion being altogether at cross purposes.

Mr. Blume draws some conclusions in his paper, and I am able to agree with all of these except the seventh, in which he

ays, "it is necessary to solidly ground the neutrals at both ceiving and generating ends of transmission lines." In my inion the word "both" is open to exception. In general, e objections which may arise from grounding the neutral sult from grounding at more than one point. Many of the lvantages of the grounded neutral are perfectly well secured ith the single ground, and many of the disadvantages are ereby avoided. Speaking in very general terms, I am clined, with extra high-voltage work, to favor Y connections ith the neutral grounded at one point only, and that is at the nerating station. The case of the Pacific Gas & Electric ompany is peculiar in that it has an extensive network, and ere is no one generating station as the logical point for ounding.

Mr. Fortescue refers to the possibilities of taking full advange in saving insulation material with the Y connection. The ansformer designed with the minimum amount of material to on a Y-connected system, with grounded neutral, might have actically no insulation at one end and full line insulation at e other end of the winding. With this form of construction it ould not be possible to make the usual factory test of two or ore times high potential for a minute. Some means might be vised to satisfy the customer that the transformer is all right spite of its inability to stand the customary high potential st.

As to the paper dealing with the Pacific Gas & Electric Comany system, Mr. Osborne has covered the principal points reting to telegraph and telephone matters which I intended to ake, and I can pass in the interest of saving time.

The contribution of Mr. Semenza refers to the Societe Conti ansmission as causing telephone and telegraph troubles. happen to be familiar with that particular case, and there, gain, the trouble is due to grounding at more than one point, turning a considerable current of triple frequency through the rth, with accompanying induction in neighboring telegraph d telephone lines. Earth currents should be avoided in layg out a-c. systems.

Mr. Lewis has given an interesting summary of the connecons in different plants in this country and other parts of the orld. This table probably represents the opinions of anufacturing engineers, quite as much as the opinions of the perating company engineers. That this table shows the Y conections to be on the increase is worthy of notice.

The series of curves and the demonstrations Mr. Montsinger as made are an interesting example of what we may sometimes o with waste products. By-products sometimes come to be of ore value than the original article of manufacture. The abily to obtain triple frequency from static transformers is, just at e present time, little more than an interesting plaything,

and its value will probably be worked out in the laboratory rather than in the commercial field. The objection to the low power factor and limited output relative to the size and cost of the apparatus, would seem to work against this being a satisfactory scheme of power transmission, though it is certainly a great convenience if you have three-phase 60-cycle current at hand to connect three static transformers, push up the density and obtain a limited supply of current at 180 cycles. Some years ago I amused myself by operating an arc lamp at 180 cycles, which, on 60 cycles, flickered objectionably. There are possibilities that a 25-cycle system might use a limited supply at 75 cycles, where the 25-cycle flicker is objectionable. These appear interesting and special applications rather than possibilities of power transmission.

In England a Mr. Taylor has been advocating this frequency change, and I believe seriously proposed the use of it on 25-cycle railroads. As this would involve three-phase generators at 8⅓ cycles, the costs and difficulties of obtaining 25 cycles in this case would appear to be much greater than the difficulties now holding for direct generation at 25 cycles, single-phase.

F. C. Green: For convenience in the discussion of this subject, the transmission system is divided into two parts: the transmission line, including high-tension switches and lightning arresters; the transformers connected to the line. Two classes of troubles are experienced with the transmission system; one affects the line and the other affects the transformers. High phase-voltages cause flash-overs of insulators, damaging the line; frequently burning off the wires and breaking the insulators. On the other hand, practically no troubles have been experienced with transformers on account of high phase-voltage. In almost every instance the trouble has been due to high frequency produced by disturbances in the line. This division into two parts seems to be a natural one.

There are many points of minor importance to the main subject, and I agree with Mr. Taylor that a great deal of the work done on the papers and a great deal of the discussion has been spent on these minor phases, such as the triple frequency and its effects. So far as abnormal voltages are concerned, or dangerously heavy currents, the triple frequency does not need any further study because, as was pointed out yesterday, these effects can be entirely eliminated by a number of methods. If, however, for any reason it should be desirable to use a system of connections which would involve triple-frequency effects, they can be eliminated as pointed out by Mr. Fortescue, in either interconnecting the phase windings, or in the interlinkage of the flux, as in the three-phase, core type transformer. But, so far as can be seen, there is no reason for using such a system of connections, because the grounded Y-delta system eliminates all of these objectionable effects.

Another minor point that is brought out in the papers bears upon electromagnetic stresses. That is a question which manufacturers particularly, and in a limited sense, operators, have been very seriously interested in. But when we study into the situation, we find that troubles resulting from electromagnetic stresses have been confined to those systems which have as their basis large turbine-driven generators feeding into underground distributing systems, and in a lesser extent, to small transformers taking power from large capacity substations. In these installations, troubles have been experienced from electromagnetic stresses, but in overhead transmission systems no troubles of consequence have been experienced. That is, the volume of these troubles is so small as to make them negligible in overhead transmission systems.

The one point that, it has seemed to me, has the greatest bearing upon the whole question, has not been treated at all in any of the papers. Perhaps we may say that a very good foundation has been laid in the papers for building up a discussion on this vital point, but all of the papers are devoted to normal frequency effects. The grounded Y-delta is clearly shown to give much lower phase-voltage stresses than the delta-delta under abnormal system conditions.

With the isolated delta, in case of arcing from line to ground, observation convinces me that not only phase stresses are much greater, but also high-frequency stresses which cause transformers to break down between coils. In this particular feature lies the most vital part of the question. With the neutral grounded, arcing from line to ground is more steady than arcing in the isolated delta system. With the grounded neutral, there is a dynamic voltage across the arc, while with the isolated delta, the voltage from line to ground practically disappears upon the establishment of the arc. Under this condition, the making and breaking of the arc occurs more frequently. Since high frequency occurs only at instants of making and breaking and not during existence of arc, it is evident that the system of connections resulting in fewer makings and breakings of the arc, is the safer.

In one of the papers the point is made that for systems of 33,000 volts and below, the isolated delta system is more desirable because it is more flexible. If it is true that under arcing from line to ground in the isolated delta system, there are more repetitions of high-frequency strains, the argument advanced in favor of the isolated delta system for 33,000 volts and below, does not hold, for the reason that an arcing ground in a system of 33,000 volts or lower would have the same tendency to produce high frequency and to cause the transformer to break down.

It is understood in this discussion that only the high-tension side of the transformers is connected in Y, and that the neutral of the Y is solidly grounded. Various other Y connections that have been enumerated are practically eliminated without discussion.

The possible use of two transformers in the delta system is advanced as an argument in favor of that system. Two transformers may be used with the grounded Y system, but not to the same extent as two transformers with the delta system; so that, even in this respect, the advantage is based upon degree rather than upon the nature of the system. The point has already been made of the great advantage in lowering the cost of transformers by having them designed for the grounded Y connection.

Another vital point in considering these two systems is the fact that with the grounded Y the location of a fault in the system is easy. Those who are familiar with the operation of plants know the importance of being able to locate troubles easily.

Mention has been made of the advantage in the delta system that one line wire can be grounded and the system continue in operation. I believe it is generally agreed that this applies only to short systems, or systems of low voltage.

P. M. Lincoln: This question of grounded neutral versus an ungrounded neutral is one which, I have always maintained, it is impossible for any man to sit down with a pad of paper and slide rule and figure out which way it should go. I think that this question is one of those which must be settled by experience, which must be settled by the man in the field, and for that reason I am very glad to read the paper by Messrs. Jollyman, Downing and Baum. I believe that the testimony of these gentlemen, operating men as they are, is of much more value and can be given greater credence than the testimony of those who simply sit down and look at this thing from the standpoint of the designing engineer. I think that it is a question which must be settled by practise rather than by the designer.

D. W. Roper: Mr. Fortescue in his paper makes a statement as follows: "In four-wire three-phase systems, where the e.m.f. is stepped up through the delta-star transformers, and three-phase power is supplied through star-delta step-down transformers, the latter, if their neutral is connected to the neutral, serve as balancers for loads taken off between neutral wires and lines." That statement is quite correct, but it gives a very bad operating condition. It is much easier to obtain balanced voltage in other ways, by regulators on the individual phase wires, if regulation of voltage is desired.

Further, if you have a three-wire transformer bank of that kind with a transformer neutral connected to the system neutral, the blowing of the fuse on one of the transformers does not interrupt the customer's service, and is likely to result in a burn-out of the other two transformers due to their overloading.

In Chicago both methods of operation have been tried. The scheme of grounding the transformer neutral to the system neutral was tried at first, but there were so many cases of trouble of that kind that the scheme was abandoned and the practise

is now universal, of connecting the three transformers for a power customer in star but leaving the neutral of the transformers entirely free from the neutral of the system.

One of the papers makes some reference to arcing grounds on a grounded neutral system, stating that they are, perhaps, not impossible, but are very rare. The system in Chicago, a four-wire, three-phase system with grounded neutral, has had a number of cases where an arcing ground has occurred and caused some disturbance. None of these have been very serious, but it is desired to call attention to the fact that such combinations were quite possible. An example may illustrate the point. A circuit operating normally, suddenly had the switch opened automatically in the station. It was tried several times, in succession, and each time it again opened automatically. A few minutes later we heard that an auto truck ran into and broke down a pole and that the primary wires had fallen down into the street. Trouble men were sent to this location to clear up the local trouble and the circuit switch was again tried and again opened automatically. Further examination disclosed the fact that a lightning arrester had broken down some distance away, say half a mile, from the scene of the place where the wires were down, and this lightning arrester trouble was undoubtedly caused by the high-frequency and high-potential disturbance due to the wires being down in the street at the first location.

F. W. Peek, Jr.: I would like to call attention to a point which, it seems to me, is a most important one, and which has been overlooked in this whole discussion. I do not believe that the success of the transmission of energy electrically depends on whether the transformers are either Y or delta connected. We have actual practical demonstration of successful transmission with both systems. Troubles do not generally *originate* due to the energy of the transmission system, but to energy external to the system impressed somewhere on the transmission line. In most cases the transmission lines are very long and there is probably not a lightning arrester within many miles of where the trouble starts. Insulators arc over. The energy of the system then enters, and adds to the trouble, as over-voltage or over-current, or both. Damage to apparatus may be due to lightning directly, or to the transient voltages or short-circuit current of the system energy following the lightning discharge.

Laying aside, for the moment, the relative merits of one system or the other, the most important point in transmission, and the one that I wish to emphasize, is the insulation of the transmission line. The transmission line should be insulated just as well as is economically possible, in order not to make lightning arresters of the insulators. When insulators arc over, the result is a short circuit or an "arcing ground." The arc is not under control. The line insulation should be such that the lightning arrester has a chance to discharge. The arc is

then under control and is suppressed before appreciable damage results.

There are many inconsistencies in the way in which transmission lines are insulated. I will take an actual line as an example. In a certain part of the country where the lightning is very severe there are two independent lines along the same right of way. One line is operated at 22,000 volts, and this has two suspension insulator disks in series, or operates at 11,000 volts per disk in terms of line voltage. The other line is a 100,000-volt line and has five disks, or 20,000 volts per disk in terms of line voltage. According to the general method of reasoning, the factor of safety of the low-voltage line is twice that of the high-voltage line (assuming good insulators). This is so in terms of the normal 60-cycle voltage, but it is not the normal voltage which starts the trouble. It is lightning. The arc-over voltages of the insulators on these lines are probably 160 kv. and 320 kv. respectively, while the puncture voltages are about 35 per cent higher. There was great surprise that all the trouble was on the low-tension 22,000-volt line, although it had a higher "factor of safety." Transient voltages induced on these lines by lightning probably range from 200,000 to 400,000 volts, with occasional voltages above the maximum of the range, and the majority below the minimum. Both lines are subjected to the same lightning voltage. The low-voltage line has practically no factor of safety in terms of the lightning voltage, as this abnormal voltage is often above 200 kv. The puncture voltage (about 420 kv.) of the higher-voltage line, except in rare instances, is greater than the lightning voltage generally induced upon the line. The factor of safety, as ordinarily expressed, has very little bearing as an indication of probable failure. In the case cited the "factor of safety" was seven on the low-voltage line and three on the high-voltage line. Either line would have operated equally well in a country free from lightning, as in California. The "factor of safety" should be much higher for low-voltage lines than for high-voltage lines when such lines are subjected to lightning. Of course, it is important to determine how far the insulation shall be carried out and what the factor of safety shall be. I have noticed in certain sections of the country, where lightning troubles are very severe, that when more than four or five disks are used in series there is very little trouble from lightning. Where a smaller number of disks are used the troubles are greater. Of course this also applies to pin type insulators, the number of disks merely indicating the value of the insulation. Line troubles decrease as the insulation is increased because the insulation breakdown voltage approaches or becomes greater than the induced lightning voltage. Arcing takes place over the arrester where it may be suppressed. Great damage is done by arcing following a lightning stroke.

The effect of the initial lightning stroke will be practically

the same with either delta or Y connection. The after effects due to arcing, etc., will, however, be different. In selecting insulators the mechanical side should not be lost sight of. Insulators may pass electrical tests very well, but develop small cracks when put in service, due to poor mechanical design. Failure occurs due to ordinary line surges. It is often, then, assumed that high voltages exist when, in reality, the insulators have become bad.

Great caution is necessary in making a diagnosis of a failure in apparatus, as transformers. Failures have often been attributed to over-voltage which were really due to the mechanical strains of over-current. Such failures may take place at the first slight over-voltage because the insulation has first been damaged mechanically by over-current. Mistakes in the opposite direction are also easily made.

It is not my intention to go far into the relative merits of either system. Either system may be a success with proper line insulation and proper operation and inspection. The choice depends a great deal upon whether there are a number of power houses and a network, or only one power house, whether reliability of service is the all-important factor and can be paid for, etc. This is especially so at low and moderate voltages, where the delta system is most often desirable on account of its greater flexibility and reliability. At very high voltages and with very long lines the advantages of the delta are lost somewhat and the grounded Y may be used. For instance, under these conditions the charging current and corona current with one line grounded may approach short-circuit current. An accidental ground on such an isolated delta system may thus cause large current to flow. This large leading current flowing through a reactance will cause abnormal voltage. The cost of the apparatus may have a bearing in favor of the grounded Y at very high voltages.

When comparisons are made of different systems in different parts of the country, to determine the relative advantages of delta or grounded Y, "shut-down" data should always be given, otherwise comparisons are almost valueless. A statement of satisfactory operation is not sufficient, as the term has decidedly not always the same meaning.

J. R. Werth: I should like to have Mr. Fortescue in summing up his paper, advise us in regard to his tabulation where he says "Y grounded direct or through resistance." I should like to know whether he has any data indicating whether any of these systems are grounded through a reactance; in other words, has the reference to the reactance been omitted because none of these systems was operated, or has it been omitted simply because he considered it not pertinent to the discussion?

Louis F. Blume: In reply to Mr. Taylor's objections to the complete association of the delta-Y connection with the grounded system, I believe that this has been inadvertently done through the emphasis on the discussion of grounded vs. isolated systems.

Obviously a grounded system must be delta-Y and a delta-delta system must be operated ungrounded. From this have arisen two questions:

1. Grounded systems vs. isolated systems.
2. In isolated systems the delta-delta connection vs. delta-Y connection.

As by far the larger number of delta-Y installations are operating with grounded neutral, and also as the first of the above questions possesses the greater importance, the term delta-Y has come to denote a grounded system.

Mr. Taylor objects also to my conclusion that "If it is desired to limit the value of potential at fundamental frequencies above ground of any part of the system to 57 per cent of line potential, it is necessary to solidly ground the neutrals at both receiving and generating ends of transmission line." I am perfectly willing to remove the word "both" in the above statement provided it is applied only to transmission lines in which the kv-a. capacity of the step-down transformer groups is practically equal to the kilovolt-amperes capacity of the step-up transformer groups, but if the step-down units are small compared with the size of the step-up units, and particularly if the step-down units are scattered over considerable territory, which is the case when a generating system is supplying power by means of a large number of feeders, it will be necessary to solidly ground the neutrals at both ends if potential stresses at fundamental frequencies are to be limited to 57 per cent of line voltage.

Mr. Semenza and Mr. Osborne have both spoken of the effect on the operation of telegraph and telephone lines of operating systems with neutral grounded. Under normal conditions of operation there is no difference between a delta-Y grounded system and an isolated delta system as far as the effect on telephone and telegraph lines is concerned, unless the grounded system carries an unbalanced load between line and ground. The latter case constitutes a four-wire system in which telephone troubles are caused by unbalanced loads. Obviously, troubles from this cause should not be given as an objection to the operation of transmission lines with grounded neutral, but should be considered only as a valid objection to the loading of three-phase systems from line to ground.

Telephone and telegraph interference resulting from third-harmonic current flowing in the ground under certain conditions of transformer operation should not be considered an objection to the grounded Y system, because, as Mr. F. C. Green has pointed out, in all properly designed transformer connections such troubles are entirely eliminated.

Mr. Peek has raised a number of interesting questions, and intimates that there can be potential disturbances on grounded systems, and also current disturbances on isolated systems. Undoubtedly this is true, and it is to be regretted that more

lefinite information concerning this feature has not been pre-ented.

In general, I agree with the various members who have said hat the papers as presented do not completely cover the question ınder discussion. There are a number of troubles which occur n transmission lines which have a very vital bearing upon the uestion, and which have only been casually mentioned. On his account it is very difficult for us at the present time to form ny definite conclusions as to the relative superiority of either ystem.

C. L. Fortescue: In closing the discussion on my paper, it eems necessary only to sum up what has been said by previous peakers, since most of the questions asked by certain speakers ıave been answered by others.

However, I will first touch on the papers by some of the ther authors, which deal with questions treated in my paper. n the paper by Messrs. Sorensen and Newton, which was ead yesterday, tests were made on Y and delta connections, ınd some very radical conclusions were drawn. I may state that have gone over these tables carefully, and find no basis for hese conclusions. I notice that many necessary data are missing. There is no information as to the primary voltage and the econdary voltage of the transformers, the type of generator, ıow it was driven, and we do not know whether the iron in the ransformers was saturated or at normal induction, in other vords, we have nothing in this paper to enable us to draw our own conclusions.

The authors' conclusions are, I might say, somewhat dog-natic. In one paragraph this statement is made:

"When transformers were made in small sizes only, particu-arly if they were shell type, there was some advantage in hav-ng the windings connected Y for the high-tension side of the bank, as this allowed a smaller number of coils and less insula-ion, because the normal strain was 57.7 per cent of that of delta-connected transformers. The increase in size of units and the provision for maximum strain where one line becomes grounded ıave made these economic advantages obsolescent, except in ome very special cases of small, high-voltage units. Hence, rom the point of design and manufacture, there is no advan-age for either Y or delta construction."

This is puzzling. I feel that I cannot agree with this state-nent. I think, now that we are getting higher voltages, even uch a little difference as a normal potential stress of 57.7 per ent of line voltage as against 87 per cent, becomes of more and nore importance.

There is one point in Mr. Blume's paper that I would like to all attention to, namely the question of operating delta banks n multiple with open delta banks. Mr. Blume says that when wo or more delta banks are operated with an open delta bank, he total capacity is somewhat lower, but that by inserting

reactance in series with the remaining phase the capacity would be considerably increased. The better way of operating such banks in multiple would be to insert reactance coils equal to the effective reactance of one transformer in the apex of each of the open delta banks. This produces in an open delta the same effect as a balanced delta connection. The banks will then divide the load as if all the systems were balanced. By inserting the proper impedance in each line of the remaining banks the delta-connected banks may be operated at full capacity without overloading the open-delta-connected banks.

In regard to the discussion on my paper, Mr. Taylor has pointed out that there is some confusion as to the manner of operating delta-delta and delta-star-connected banks of transformers. There seems to be an impression in the minds of a great many of the people who have discussed this matter that delta-star-connected banks necessitate grounded neutral. I want to emphasize what Mr. Taylor has already said, namely, that the delta-star can be operated just as well without the grounded neutral, and it also has some other decided advantages which have been sufficiently dealt with in my paper. The points which Mr. Green intimated had not been touched on are also referred to in the paper.

The characteristics of the transmission lines and local conditions, as Mr. Peek has brought out, are the predominating influences, so that in some cases in the delta connection the troubles are current troubles as against the usual voltage troubles, and in some cases in the Y connection the troubles are voltage troubles as against current troubles.

In connection with telephone troubles in grounded systems, the delta-star step-up transformer almost entirely eliminates the third harmonic. It does not eliminate it entirely, because of the drop through the effective primary impedance, due to the magnetizing current, which has harmonics of the third group. This produces a small third-harmonic pulsation in the neutral, which may have an amplitude of the order of $\frac{1}{2}$ per cent, or less, of the line voltage, but is not of sufficient magnitude usually to produce telephone troubles.

I think, as Mr. Blume has pointed out, that the telephone troubles in star systems have been due largely to Y-Y-connected systems in which the neutral of the Y is connected with the neutral of the generator. The generator nearly always has a triple-harmonic component in the voltage between neutral and line, which is transformed in the secondary, and the charging current to ground due to this component even when small may be extremely large, as has been pointed out in the discussion, and cause telephone troubles. Also it is a very common practise, at least in the West, in sparsely populated districts, to load between one wire and ground, which is also very bad practise as far as telephone circuits are concerned.

To sum up, it seems that sufficient regard has not been paid

to the advantages of the delta-Y system ungrounded as against the delta-delta system. It has decided advantages, which should be given consideration. In fact, the higher the voltage, the greater are the resulting advantages. In my paper I have stated that, if the voltage is above 44,000, generally speaking, the star connection grounded or ungrounded has the advantage.

There was a question asked as to the use of reactance in series with the neutral to limit the short-circuit current. I have no data as to whether any of these systems mentioned use reactances or not. About seven or eight years ago, a system came under my observation in which the neutral point of a star-connected auto-transformer was to be grounded. The neutral point was first of all solidly grounded, which resulted in considerable disturbance in neighboring telephone circuits. Grounding through reactance was next tried and much to the surprise of the experimenters the disturbance was increased; the more reactance they put in, the more charging current they obtained. I rather think that a reactance is not the proper thing through which to ground the neutral point.

I think Mr. Roper made the statement that it was inadvisable to connect the neutral point of star-delta step-down transformers to the neutral wire in the four-wire system. Generally, the four-wire system is operated from the generator, and since a triple harmonic is usually present between the neutral wire and the lines, if the neutrals of generator and transformer bank are connected through this wire a third harmonic will circulate, which is a bad feature. "In four-wire three-phase systems, where the e.m.f. is stepped up through delta-star transformers and three-phase power is supplied through star-delta step-down transformers, the latter, if their neutral be connected to the neutral wire, serve as balancers for loads taken off between neutral wires and lines." The delta-star bank of step-up transformers eliminates the third harmonic, and permits the breaker to open when there is a ground or short circuit on the customer's line.

Max H. Collbohm (by letter): The papers presented, discussing the relative merits of grounded and ungrounded transmission systems, seem to be quite generally in favor of the grounded system, both from the standpoint of safety to equipment and convenience of operation. The writer's experience with a number of grounded and ungrounded transmission systems has prompted him likewise to give preference to the grounded system, provided certain precautions are taken to guard against service interruptions in case of an accidental ground on the line which ordinarily would cause a short circuit on one phase and open the line switch.

In a recent article* the writer discussed a scheme for protecting a grounded system against service interruption, which consists of a metallic grounding rheostat between the transformer neutral

*"Service Continuity in Grounded Transmission Systems." Max H. Collbohm, *Electrical World*, April 18, 1914.

and ground for reducing the current through the ground, and a special instantaneous circuit-opening relay inserted in the tripping circuit of the line switches and energized from the secondary of a current transformer, the primary of which is connected in the lead from the grounding rheostat to ground. Through this arrangement an automatic opening of the line switches by an accidental ground on the line is prevented, as the special circuit-opening relay energized by the ground current opens the tripping circuit of the line switches before the inverse-time overload relays of the line switches have closed their contacts. An ammeter, alarm bell and signal lamp inform the attendant of the existence and severity of the ground and permit him to isolate the line in trouble without service interruption.

The article mentioned gives a description of other protective features as well, and records also the actual operating results obtained during the lightning season of 1913 in the system of the Peninsular Power Co., Iron Mountain, Mich. (66,000 volts, 40 miles) which had been equipped with the protective equipment described in said article. As will be noted, the system went through nineteen lightning storms of more or less severity with only four seconds of interruption due to lightning, or practically none at all. It is a significant fact that not even a single insulator became damaged by lightning in spite of a large number of accidental grounds over them, which fact is evidently due to the installation of upper and lower arcing rods on each string of insulators.

These results seem to indicate that practically absolute continuity of service can be maintained in a grounded system, if properly equipped, with perfect safety to the equipment and convenience of operation.

Presented at the 296th Meeting of the American Institute of Electrical Engineers, Pittsfield, Mass., May 29, 1914.

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RELATIVE MERITS OF Y AND DELTA CONNECTION FOR ALTERNATORS

BY T. S. EDEN

ABSTRACT OF PAPER

The main advantages obtained with the Y connection are as follows:

(1) It is possible to bring out a lead from the neutral point of the winding, which is useful for various purposes.

(2) The cost is less than with the delta connection, requiring approximately 58 per cent of the turns.

(3) It is not possible for circulating currents of triple frequency to flow in the windings.

The delta connection does not appear to have any advantages except as a convenience in design for certain voltages. When used, proper precautions must be exercised in the design to eliminate excessive circulating currents.

THE FLEXIBILITY in design of three-phase machines, as compared with two-phase, lies in the possibility of using either the Y or delta connection.

It might be expected that either connection would be used indiscriminately, depending on which worked out best for the case in hand.

However, it is probably safe to say that over ninety per cent of the three-phase generators built are Y-connected.

The other cases are those in which, due to limitations in design as regards specified output, voltage, etc., the delta connection permits the use of standard frames and tools, thus avoiding development. A few cases will also arise where customer's specifications call for the delta connection.

Some of the advantages of the Y connection are as follows:

(1) The possibility of bringing out a lead for various uses from the neutral of the winding.

This lead may be grounded. It may be used as the return in a four-wire system, giving, with a 240-volt generator, the voltage between the neutral and the end of each phase for incandescent lighting; similarly, on a 4000-volt generator, giving 2300 volts for use with standard transformers for three-phase four-wire

systems of distribution. In this latter case the neutral is generally grounded. This system is used in many large cities.

(2) The Y connection gives the required voltage with 58 per cent of the turns required by the delta connection. This is a large factor in cost, especially in machines of high voltage and large numbers of turns per coil, where the expense of internal insulation increases rapidly.

(3) In a Y-connected machine, with ungrounded neutral, it is impossible for currents of triple frequency or multiples of triple frequency to flow, since the third harmonics, existing in the two legs of the Y winding which are in series between a pair of terminals, are opposed to each other and of equal value, thus neutralizing one another.

In a delta-connected machine, the triple harmonics are in phase with each other, and will send triple-frequency currents through the three phases in series of the closed delta. These currents are internal in the windings, the e.m.f. which causes them to flow being short-circuited in the closed delta, not appearing in the e.m.f. measured between terminals.

These circulating currents may be of great magnitude, entailing large I^2R losses in the windings and corresponding loss of efficiency.

(4) In general, for the average alternator, the e.m.f. wave of the Y-connected winding is nearer a true sine than that of the delta-connected generator.

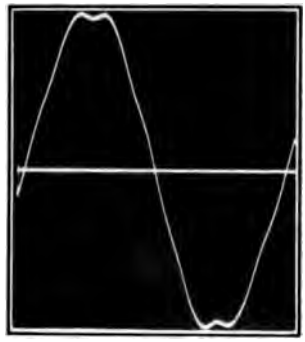
(5) The use of the grounded neutral reduces the potential strain on the insulation of the windings, permitting reduced thickness of insulation.

The above indicates the merits of the Y connection.

On the other hand, the delta connection does not appear to have any advantages. When used, care must be exercised in design, paying attention to the percentage of pole-face width to pole pitch, shape of pole face, saturation of the magnetic circuit, etc.

Fig. 1 gives the wave shape of the e.m.f. on closed delta of a 900-kv-a., 25-cycle, 400-volt unit, in which it was found that the circulating current at excitation for no-load full voltage was 83 per cent of full load current.

At 75, 87.5, 100 and 112.5 per cent of full voltage no-load, the circulating current was found to be 59, 69, 83 and 107 per cent, respectively, of full load current.



[EDEN]

FIG. 1—POTENTIAL WAVE OF 900-KV-A. 25-CYCLE, 400-VOLT GENERATOR, CLOSED " DELTA ".

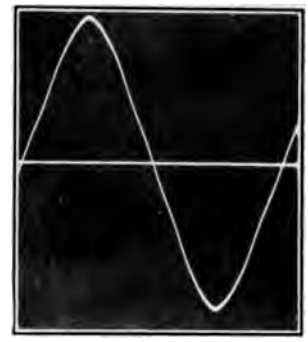


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FIG. 2—POTENTIAL WAVE OF 900-KV-A., 25-CYCLE, 400-VOLT GENERATOR, OPEN " DELTA ".

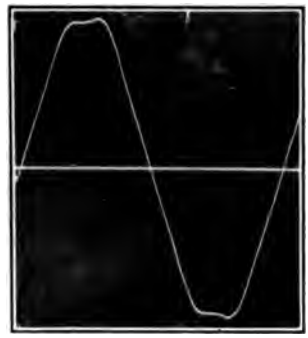

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FIG. 3—POTENTIAL WAVE OF 7.5-KV-A., 60-CYCLE, 110-VOLT GENERATOR CLOSED " DELTA ".

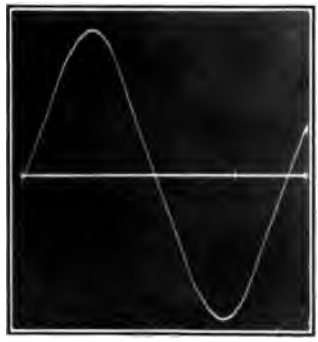

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FIG. 4—POTENTIAL WAVE OF 7.5-KV-A., 60-CYCLE, 110-VOLT GENERATOR, OPEN " DELTA ".

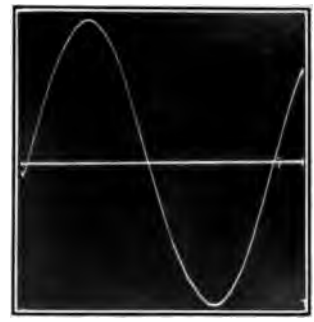

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FIG. 5—POTENTIAL WAVE OF 7.5-KV-A., 60-CYCLE, 110-VOLT GENERATOR, ACROSS TERMINALS CONNECTED Y.

The analysis of this wave shape shows the equation of the curve to be

$$
\begin{aligned}
E = &+ 99.9 \sin(\alpha - 0.01 \text{ deg.}) \\
&+ 1.0 \sin(5\alpha + 36 \text{ deg.}) \\
&- 1.8 \sin(5\alpha + 4 \text{ deg.}) \\
&+ 2.9 \sin(7\alpha - 16 \text{ deg.}) \\
&+ 0.2 \sin(9\alpha + 59 \text{ deg.}) \\
&- 1.1 \sin(11\alpha + 72 \text{ deg.}) \\
&- 0.3 \sin(13\alpha - 45 \text{ deg.})
\end{aligned}
$$

Similarly, Fig. 2 shows the wave shape of e.m.f. taken across one leg of the delta, one corner of the delta being open.

The analysis of this curve gives the equation

$$
\begin{aligned}
E = &\ 99.9 \sin(\alpha - 0.1 \text{ deg.}) \\
&- 5.9 \sin(3\alpha - 9 \text{ deg.}) \\
&+ 0.3 \sin(5\alpha + 28 \text{ deg.}) \\
&- 0.1 \sin(7\alpha - 86 \text{ deg.}) \\
&+ 1.1 \sin(9\alpha + 8 \text{ deg.}) \\
&+ 0.1 \sin(11\alpha + 0 \text{ deg.}) \\
&+ \ \ 0 \sin(13\alpha + 0 \text{ deg.})
\end{aligned}
$$

In the former the percentage of third harmonic is small as compared with the latter, the e.m.f. being used up in overcoming the internal impedance of the machine. However, the fifth and seventh are strong, being produced by the pulsations of the field set up by the circulating current in the delta. The latter shows a third harmonic approximately 6 per cent of the fundamental, the others being practically negligible.

The Y connection constructed by adding two waves like Fig. 2, displacing them 60 deg., gives practically a sine curve. The use of a Y connection in this instance would have effected a saving of over 1 per cent in efficiency at full load.

Similarly, curves in Figs. 3, 4 and 5 show e.m.f. waves of closed delta, open delta and Y connection on a 7.5-kw. alternator in which the circulating current was a large percentage of full load current.

A further example of the effect of saturation on circulating current is seen in the following table, made up from tests of a 3000-kv-a., 6600-volt, 112-rev. per min., 60-cycle generator, connected delta for testing purposes.

Per Cent Full Volts per Phase	Circulating Current in Per Cent of Full Load Current
57	6
77	7.7
87	8
94	7.7
107	3
115	0

By using a $66\frac{2}{3}$ per cent pitch winding, with the delta connection, the third and multiples of the third harmonic are eliminated. (See TRANS. A. I. E. E., Vol. 28 (1909) page 1064.)

Thus in a 2500-kv-a., 2300-volt, 133-rev. per min., 60-cycle generator delta-connected, using $66\frac{2}{3}$ per cent pitch, an ammeter

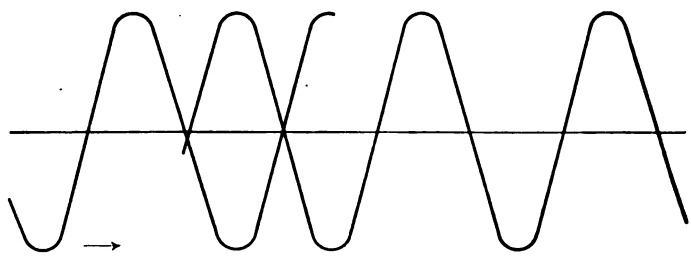

FIG. 6—POTENTIAL WAVE OF 2500-KV-A., 60-CYCLE, 2300-VOLT GENERATOR, OPEN DELTA.

in the corner of the delta gave no reading. The wave shape taken across one leg of the winding, with the delta open, is shown in Fig. 6.

It would therefore seem that from the standpoint of the designer, the Y connection is the safest to use and that great care must be exercised in using the delta connection.

Presented at the 296th meeting of the American Institute of Electrical Engineers, Pittsfield, Mass., May 29th, 1914.

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DELTA AND Y CONNECTIONS FOR RAILWAY TRANSMISSION AND DISTRIBUTION

BY CASSIUS M. DAVIS

ABSTRACT OF PAPER

Transformer connections under the following three conditions are discussed:

The railway (1) purchases power; (2) builds and operates the generating and transmission systems; (3)purchases power and in addition builds and operates a secondary transmission system.

The choice between delta and Y connection is frequently determined by purely economic considerations. However, it is common practise to use the delta connection on both the high- and low-tension sides of transformers, except in the case of six-phase converters, where the diametrical connection on the low-tension side is the rule. Synchronous converter substations employing two machines in series for high-voltage d-c. railways, are frequently operated from single banks of transformers, which have double windings on the low-tension sides. Methods of starting have little effect upon transformer connections except in the case of six-phase converters. Transformer connections are seldom important electrically in single-phase and three-phase railway systems. A secondary distribution system may at first be delta-connected and later changed over to Y connection to obtain better voltage regulation.

THERE are three general problems which present themselves for any railway system. They are classed as follows:

1. The railway purchases power.

2. The railway builds and operates the generating and transmission systems.

3. The railway purchases power and in addition builds and operates a secondary transmission system.

These conditions to a certain extent affect the choice of transformer connections, the use of delta or Y frequently being determined from purely economical standpoints. That is, it may be cheaper to install transformers with delta-connected primaries for a given synchronous converter than with Y-connected primaries.

A further condition, which may or may not have a bearing on the system of connection, is the fact that interurban lines and railway electrifications require substations which are spaced

at an ever-increasing distance from the generating station. They are frequently tapped off the same transmission line.

1. *Power Purchased by the Railway.* The railway has no choice as to the manner in which the supply system is connected. It must accept the power from either a delta- or a Y-connected transmission line, grounded or ungrounded.

General practise favors the delta connection on the high-tension side of the substation transformers regardless of the arrangement of the transmission system. The principal argument is that a three-phase bank of transformers may be operated open delta in emergencies at 58 per cent of its total normal output.

The connection on the low-tension side depends upon the type of distribution and on the kinds of transforming or converting apparatus.

For synchronous-converter substations with three-phase converters the delta connection is usual. This holds for machines of all voltages.

For synchronous-converter substations with six-phase converters the diametrical is the rule, since with either the double delta or the double Y, two secondary windings are required, while the diametrical connection needs but one secondary winding.

Synchronous-converter substations operating two machines in series for voltages from 1200 to 2400, and when supplied from single transformer banks, always have double secondaries connected delta for three-phase converters, and diametrical for six-phase machines.

Railway work seldom requires the neutral to be brought out. Where it is required, however, the Y, the "zig-zag" or the diametrical connection must be used, with proper provision for starting.

Motors for motor-generator sets may receive power from transformer secondaries connected either delta or Y. There is little choice between the two connections. Substations employing motor-generator sets frequently have a low-tension a-c. bus which is fed from transformers where the secondary connection is governed by conditions extraneous to railway operation. For example, the low-tension a-c. bus may form a part of an a-c. network, the neutral of which it is desirable to ground.

The methods of starting are controlled somewhat by the

secondary connection. Synchronous motors and converters are conveniently started from reduced voltage taps. If the transformers are delta-connected, starting can easily be accomplished on open delta. If they are Y-connected, the machines can be started at reduced Y voltage. With six-phase converters, the starting connections become very complicated with either the double delta or the double Y connection, especially with the machines of large output. Synchronous converters are seldom started by means of compensators for the reason that each converter is usually provided with its own bank of transformers, the taps of which are far less expensive than a separate compensator.

Starting from the d-c. side, or by means of a direct-connected starting motor, obviously has no bearing on the transformer connections and hence is omitted from this discussion.

The possibility of grounds and short circuits on the trolley or third rail has no effect upon the choice of transformer connections.

Since energy for single-phase railways is usually transmitted single-phase, the question of transformer connections does not come up for discussion. Even where the transmission is polyphase, the low-tension distribution for a single-phase railway system is taken from the transmission line through single-phase transformers. Thus, as far as the present discussion is concerned, there is no choice involved between delta and Y.

Either delta or Y connections may be used for three-phase railways. The choice would be governed by conditions existing in each individual case.

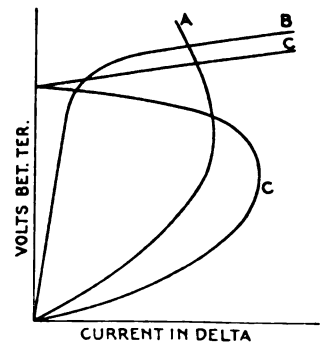
2. *Generating System Built and Operated by the Railway.* This problem involves the general question of delta versus Y connection. It is not necessary to go into a discussion of the advantages and disadvantages of either system since these points are brought out in other papers presented at this meeting. A railway load does not differ in essentials from any other load, and the same arguments relative to the choice of system apply here as well as to any other type of load.

In any system adopted, due provision should be made for extensions. This is especially true in railway electrifications where usually only a few miles constitute the initial electrification which ultimately may extend several hundred miles. Transmission lines for this type of load may be tapped at frequent intervals. This fact, it would seem, would tend to prevent,

thus giving 138 volts, which is frequently too high for lighting purposes.

The second limited advantage of delta connection applies in large machines wound for low voltages. For example, in a 2000-kv-a., 240-volt machine, the winding with star connection would be extremely difficult; it may be almost impossible. The delta connection lends itself far more readily, since it permits of more turns, the difficulty being to employ a reasonably large number of turns per phase.

The third limited advantage occurs when we endeavor to use existing parts, such as existing punchings, for a voltage for which the machine has not previously been wound, and it actually simplifies the connection rather than complicates it to use delta rather than star. For example, we may find for a certain voltage we want around $1\frac{3}{4}$ conductors per slot or equivalent thereof, for star connections. This would require 14 conductors per slot, 8 circuits, for a two-layer winding, or 7 conductors per slot, 4 circuits, for a single-layer winding. For delta connection we could use either 6 conductors, 2 circuit, or 3 conductors, 1 circuit, thus greatly simplifying the winding.



Mr. Eden shows in his oscillogram records, and in the subsequent analysis of the waves, how the delta current may vary. This refers to one or two examples, and does not cover the many cases which may arise. There is, possibly, nothing so erratic as the circulating current in the delta in the alternator. In some cases the delta current may be a curve like that shown as "A." The most common form of delta current is somewhat similar to that of a saturation curve, although usually the knee is more marked, as in "B." I have known one case in which the current rose gradually, dropped to zero and then rapidly rose again as in "C". I shall not take the time to explain these peculiarities. Although I have not had opportunity to check experimentally, I believe that the curve of delta current in delta-connected transformers varies as much as in delta-connected alternators.

Mr. Eden shows how the delta current may be reduced, or practically eliminated, by using a $\frac{2}{3}$ pitch winding. I do not think that that is the only way in which it can be reduced. For example, by inserting a sufficient amount of impedance at the apices of the delta, and tapping these impedances at their mid points, one can greatly reduce the amount of circulating current. The same effect can be accomplished by the use of magnetic wedges in the machine, which increase the internal reactance. We can, by carefully proportioning the parts of the

magnetic circuit, (for example, by carefully designing the shapes of the pole shoes), also greatly reduce the amount of circulating current. In some cases it may be an actual hardship to use a $\frac{2}{3}$ pitch winding, because this means that a greater amount of copper must be used per slot than if the full pitch winding were employed, and for this there may not be sufficient slot space where existing parts are used.

I also want to point out that circulating current is subject to change with load and with power factor. The circulating current which is ordinarily measured is that which flows when there is no load on the machine, and as soon as we put a load on, the wave form is altered. At zero power factor one gets an entirely different wave than that which obtains at unity power factor. The distortion of the magnetic field unquestionably also distorts the electromotive force wave. That may introduce harmonics which were not present before, or, if present, were probably in the wave to a different degree, and may consequently materially alter the magnitude of the circulating current. Therefore, even though the circulating current was negligible at no load, it may not be negligible at full load, or vice versa. This is something that one must guard against in large machines as they are designed at present; that is, with poor regulation, and comparatively small air gaps, the flux distortion is much greater than it was in machines of some ten years ago, when they had close regulation, comparatively long air gaps, and the flux distortion was comparatively small. I think possibly that also in delta-connected transformers, the load and power factor may have some influence upon the circulating current. I have not given this much thought, and I suggest this in order that those who have been working on this line may investigate further.

The author calls attention to the effect of the circulating current upon efficiency. I want to point out that I do not think efficiency is nearly so important in this connection as temperature. Circulation current may introduce temperature rises, which may be of serious magnitude; especially would this be the case under load if the distortion of the flux were such as to cause a considerable circulating current. In such a machine, then, the only proper way that one could make an accurate temperature run would be to put full load on it.

E. G. Merrick: I would like to make a few remarks in connection with Mr. Eden's paper, with especial reference to turbo-alternators. Mr. Eden and Mr. Fechheimer pointed out that in the salient-pole machine, harmonics can be reduced very considerably by the proper proportioning of the pole faces. For the usual ratios of pole arc to pole pitch this gives a maximum gap at the pole tips which is about double the minimum gap. In the modern turbo-alternator, which is now usually built with a cylindrical rotor, we have a uniform air gap and the above result must be obtained in another way.

A fully distributed field winding, one which would correspond

to the winding of a direct-current armature, will produce a triangular magnetomotive force curve, the apex of which corresponds with the center of the pole. On the other hand an entirely concentrated winding will give a rectangular magnetomotive force curve.

It is evident that by proper proportioning of the wound and unwound portions of the pole pitch between these limits we we can get a magnetomotive force curve which approaches very closely to a sine wave.

Neglecting saturation, any harmonics which exist in the magnetomotive force curve will appear in the flux wave, and again, these harmonics will appear in the same way in the electromotive force curve, modified by their respective winding factors.

If the ideal rotor winding is obtained—viz., that in which the wound portion occupies two-thirds of the pole pitch, we will get practically a sine curve of m.m.f. and the third harmonic and its multiples will disappear. It is therefore usually possible to design the non-salient pole type of machine so that it can be connected either in delta or in star.

Mr. Fechheimer has just made a statement in regard to the third harmonic being influenced by the load. Tests on the non-salient pole type of machine do not, however, indicate such an effect. This is shown as follows: Measurements on a delta-connected machine under load indicate a certain current X in each line and a current Y in the delta, Y being greater than X on account of the additional current due to the third harmonic. At no-load and normal voltage we get a value Z for the circulating current in the closed delta and the combined currents X and Z will equal the above current Y. This would indicate that the value of the circulating current due to the third harmonic has not been changed appreciably by the load.

C. J. Fechheimer: How many machines was that carried out on?

E. G. Merrick: I have tried it on a number of different machines.

C. J. Fechheimer: What kind of load?

E. G. Merrick: On non-inductive load.

C. J. Fechheimer: That is contrary to my observations.

E. G. Merrick: In each instance the calculated results have come within the limits of error of reading.

C. J. Fechheimer: You must recognize the fact that the circulating current due to higher harmonics is not directly additive to the load current. I see you combine it in quadrature.

T. S. Eden: There is no question that by using a proper width of pole face, in per cent of pole pitch, the third harmonic can be avoided. The alternator, on the wave forms of which I made an investigation and reported the results in the paper, was one in which the percentage of pole face to pole pitch was only 52 per cent. Had this been $\frac{2}{3}$, the third harmonic current would have been largely eliminated, and there would not be any such value as 60 per cent in the fundamental.

R. E. Doherty: There is one point that just occurred to me in the way of an explanation of the discrepancy between the observations of Mr. Fechheimer and Mr. Merrick. Mr. Fechheimer says that he has noted no change in effect of the circulating current in the delta under load, and Mr. Merrick has noted that it has been appreciable. I wonder if the possible explanation is that since this change that Mr. Fechheimer pointed out is due to a change in relation of the center line of flux from the center line of the pole, whether the use of different proportions of minimum gap to maximum gap in the two machines on which this thing had been tried out does not account for the discrepancy in observations? In the machines Mr. Merrick has referred to, he has pointed out that the maximum gap was something like twice the minimum gap. I wonder if this relation holds in the machines Mr. Fechheimer referred to.

C. J. Fechheimer: It does not.

E. G. Merrick: The tests I referred to were on smooth, cylindrical rotors, turbo-alternators.

C. J. Fechheimer: If the armature reaction, even in the turbo-generator in which the winding on the rotor is distributed, were sufficient to distort the flux, I should think the effect of the circulating current would be altered in most cases by change in load. I have not made any observations myself on turbo-generators in this regard, so I am not able to speak from experience. I am only theorizing. The machines I had in mind were definite pole alternators, in which the minimum air gap was but little less than the maximum air gap. By minimum air gap, I mean the gap at the middle of the pole, and the maximum at the edges of the pole.

R. E. Doherty: The condition, as I see it, is due less to difference in armature reaction than the spread of the exciting coils, which increase in reluctance in one case from the center of the pole to the edge, this difference being greater where the ratio of minimum to maximum gap is large than where it is more nearly uniform. The distorting effect of armature reaction would shift the flux a great deal more in the uniform gap.

Cassius M. Davis: I wonder if there is not a simpler explanation for that. In the transformer the triple harmonic exists whether there is load or no load, and the triple harmonic exists in about the same magnitude. It is not so noticeable in its effect upon the wave shape at load because the load current is so much greater than the triple harmonic current. Leaving aside the effect of flux distortion, I wonder if the circulating current in the delta is not there all the time in about the same magnitude, whether there is a load or no load, but in measuring the voltage or taking an oscillogram across the phases, the wave appears smoother at the load, due to the reactance drop through the armature winding, while the triple harmonic may still exist there. This is analogous to the exciting current of a transformer, which stays about the same, regardless

of the load, and is too small to appear in an oscillogram taken across the terminals.

John B. Taylor: Bearing on circulating current losses in a delta-connected generator, I recall tests measuring directly the triple-frequency voltages in windings of a generator by connecting in Y and reading between common connection or "neutral" of generator and a true or stable neutral of transformer bank. These triple-frequency readings changed as normal frequency load on the generator was increased or decreased.

With a delta-connected generator, I suggest measurement by ammeter or oscillograph of the three currents (two in generator windings and one in external lead), at a corner of the delta. By this means, amount of circulating currents at different loads and excitations may be determined.

Selby Haar: I speak in defence of the delta connection from the operator's standpoint. As long as conditions are likely to arise in service which make it necessary to operate damaged but partly serviceable generators temporarily, we cannot spare the delta connection. Anyone who has been able to maintain three-phase service with two transformers connected in open delta will agree with this statement.

Mr. Eden reports 83 per cent of normal load current in one case. This current could be reduced to a harmless value by inserting reactances which preferably should exhibit a proportionally higher reactance to harmonics than to the fundamental of the current wave; in view of some present tendencies of design, the increased reactance at normal frequency would not be altogether undesirable. Each reactance would consist of an iron core wound with a coil of several turns, from the middle one of which a tap is brought out. Each corner of the delta is opened, and the two leads connected to the ends of a reactance coil, the tap being connected to the line. Suppose such a coil to have $2n$ turns, then the current at fundamental frequency in one group of n turns (on one side of the tap) is 120 degrees out of phase with the current in the other n turns, and the resultant magnetomotive force of both will equal In, taking I as the current per phase. The current of triple frequency, however, flows in the same direction and is of the same phase in both parts of the coil, so that at current I, the magnetomotive force is $2In$. Thus the reactance (below saturation of the iron) should be 6 times as great for the triple harmonic, and 18 times as great for the 9th harmonic as for the fundamental. Of course the saving realized by the smaller circulating current in the generator is partly offset by the iron and copper losses in the reactances.

Where there are no insulation difficulties on account of high voltages nor space restrictions (as to shape and sizes of reactances) to contend with, the three coils may be wound on one core. Now the odd harmonics in the wave of e.m.f. (or current)

may be divided into three groups of the orders $3a$, $6a-1$, and $6a+1$, where a is any positive integer. The resultant magnetomotive force of these three coils, when supplied with balanced three-phase currents at fundamental, $6a-1$, and $6a+1$ harmonic frequencies, is zero, while the three individual triple, ninefold, fifteenfold, etc., frequency, magnetomotive forces are in phase. Hence the impedance of such a device to all harmonics of order not a multiple of 3 would consist of resistance only. Since, as stated, all harmonics above the third were practically negligible, the effect of such a coil should be very marked in this case. It would be interesting, as a check on this conclusion, if Mr. Eden could supply an oscillogram of the circulating current in one of these machines; it should show only the $3a$ harmonics. We should not give up the delta connection simply because it is difficult to design a good delta-connected generator.

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THE EVOLUTION OF THE INSTITUTE AND OF ITS MEMBERS

President's Address

BY C. O. MAILLOUX

INTRODUCTION

THE constitution of this Institute prescribes that the president "shall deliver an address at the annual convention." The duty thereby assigned to the president becomes one of his last official ones, when the annual convention falls so near the end of the term of office, as it has in the last few years.

The realization of the approaching end of his term of office made one of my distinguished predecessors feel that his presidential address was a sort of "swan song." It is a cause for congratulation both to the Institute and to him that he has since then contributed several other very good "songs" which have received great applause both here and abroad; and his many friends and admirers all rejoice over the good prospects of his being heard from again, many, many times. The fact that so many of our past-presidents have retained a great interest in the affairs and welfare of the Institute, and have continued to work most loyally and zealously in its service, makes me feel that it would be misleading to ascribe a "valedictory" character to the president's address. I am very certainly not inclined to regard it, in my own case, as an incident of "leave-taking," since I feel the strongest desire and disposition to continue to serve the Institute to the best of my ability after I return to the ranks. I prefer to regard it in the light of a graduation-thesis, constituting one of the requirements for the "honorary degree" of "past-president."

THE DEVELOPMENT AND ACTIVITY OF THE INSTITUTE

The wondrous activity of this Institute, the enormous amount and the magnificent quality of the work which it does each year, are so full of interest and so worthy of attention, that they would easily furnish both the pretext and the inspiration for an interest-

ing and instructive address. To one who, like myself, had the privilege of " enlisting " as one of the founders, and who holds the diploma of charter-member of this Institute, its growth, its expansion, its work, and its achievements have been, from the beginning, and still continue to be, sources of increasing wonder and astonishment. There is, in truth, reason for us to be proud, even to the degree of exultation, over the fact that the American Institute of Electrical Engineers, the youngest in the family of national engineering societies in the United States, has pushed its way to the very first place among them all, not alone in point of membership, but in respect to its subsidiary centers of activity, *i.e.*, its Sections and Branches; also, and more especially, in respect to the number and the character of the contributions to original knowledge of which it has been the depositary and the means of dissemination; also in respect to the important role which it has played and the great influence which it has exerted in the entire world, in connection with questions of electrical units and standards and other matters calling for international conference and agreement. There is still at least one other respect in which it need not fear, but could challenge, comparison, (even if the list also included the sister societies in the rest of the world), namely, the proportion of active workers, *i.e.*, the proportion of members who give material evidence of their interest in the work, welfare and development of the Institute by making sacrifices not only of time, but of money through their zeal in its service. So far as I know, there is no other engineering or scientific society in the world which has the good fortune to have at its disposal, fre of cost, the services of so many high-grade men.

This willingness and readiness to serve are evident in all the Sections and Branches of the Institute; and that is precisely what has made the plan of forming Sections and Branches so successful. It is in connection with the activities of the central body of the Institute, however, that the results of the devotion of our active members are most apparent and significant. Each month, men who hold most important positions gather at the Institute headquarters from all points, far and near—many of them coming a thousand miles, and some even a still longer distance—to attend meetings of directors and of committees. In general, the attendance at these meetings is surprisingly large. Frequently, there are many different committees holding meetings. Some of these meetings may begin a day or two before, and some may not be over until a day or two after " In-

stitute day." Very often, the committee works until a late hour in the evening, and, occasionally, it continues its work the next day. On at least two occasions, one of our most important committees, the Standards Committee, has been in session day and night for more than three days in succession.

The enthusiasm and the energy of these faithful and devoted workers, their evident desire to collaborate and cooperate to the highest advantage for the good of the cause, cannot fail to excite both wonder and admiration. The interesting and significant thing is that these men work with the same earnest attention and the same desire to produce substantial and useful results that they manifest in dealing with matters of most profound personal interest and importance. Not only is this high grade work done voluntarily, but the men literally pay for the privilege of doing it. The time and traveling expenses of some of these men amount to a large figure at the end of the year; and some of them have been serving the Institute, at that cost, for many years. Moreover, in many cases, notably in the case of chairmen and secretaries of committees, the work done at meetings is in reality only a small part of the total work done by them, which includes a great amount of correspondence. I have deemed it a duty to refer to the amount and the quality of the work that is done by the members without cost to the Institute, for two reasons: First, because the fact that there are so many devoted, earnest, faithful workers rendering such valuable services at more or less great personal sacrifice and expense may not be as well known to the membership at large and as much appreciated as it deserves to be; second, because I wish to pay a well deserved tribute of praise and to do honor to these men. It is a duty and it is also a great pleasure to me to pay a tribute of appreciation and of gratitude, here, for the Institute and for myself, to all these faithful, self-sacrificing workers, to whose zeal, loyalty, energy and generosity, the Institute is so much indebted for its success and for the reputation which it has achieved both here and abroad. It is precisely here, in my opinion, that we find the true explanation of the phenomenal growth and development of the Institute. It has often been remarked, by persons who are informed about the activities of the Institute, especially about the work of its important technical and special committees, that if the time and effort devoted to this work had to be paid for, even at bare cost, the Institute would need an enormous increase in revenue to carry it on. This is a modest

The technical committees of the Institute represent an honest and earnest effort which has been made—and with considerable success—to secure diversity in technical work and to give scope, individuality, and recognition to the various specialties and activities of the members or of groups of members of the Institute while avoiding their segregation into distinct small societies.

Each of our technical committees has the resources, the authority, and the prestige of the whole Institute; and every member of the Institute receives the full benefit of the activity and of the work done by the specialists constituting the committee. In effect, the result is the same as if every member belonged to a number of distinct societies specializing in certain subjects. This point is deserving of attention, as disclosing a feature which is not as well understood or as fully appreciated as it deserves, and as suggesting a field for further development.

So far as concerns the specialists themselves who take part in the activities of the technical committees, they are relieved of the responsibilities and burdens of keeping a small society alive to give scant support and limited publicity to their work as specialists. It is obvious that their work reaches a much larger number of people and does much more good when done under the auspices of the Institute. The Institute plan is based upon the principle that "in union there is strength," and on the economic advantages resulting from concentration of organization and administration. This plan fosters diversity by permitting activity in many directions that would not warrant the formation and could not maintain the existence of separate societies, and, for other specialties which could only hope to maintain a separate society on a small scale, and in a more or less precarious way, it offers a larger field and secures a larger audience, which, as we all know, is a consideration of the highest importance, because it gives the best incentive and is the best stimulus for doing work of the highest grade.

The preceding considerations reveal certain fundamental principles of efficiency and economy with which electrical engineers are all very familiar, namely, the importance of high values for the "diversity" and "load" factors in central stations. The Institute is, in effect, a kind of central station for the generation and distribution of a certain kind of electric "power" which is useful in the production of electrical "work" of greatly diversified character and of extreme importance, as a whole, to the vocation of the electrical engineer, and to the standing and the

advance of the electrical engineering profession. The analogy is perfect; centralization of activity and the superimposition of load-curves,—as the result of increasing the diversity-factor,—lead to a higher load-factor in the Institute, and in about the same way as in an ordinary electric power-station.

The Institute has abundantly realized its objects as we find them stated in the constitution, namely, "The advancement of the theory and practise of electrical engineering and of the allied arts and sciences, and the maintenance of high professional standing among its members." It has amply fulfilled its mission and its trust as the representative of the profession of electrical engineering in the broadest and most comprehensive sense. It gives shelter and support, encouragement and standing, to all the branches and specialties of the profession that are worthy. Its numerous Sections and Branches in North America, and its many groups of specialists working in various electrical fields, suggest a federation of states and territories, whose citizens are amalgamated into a coherent mass, in accordance with the old motto, "E pluribus unum," which the Institute exemplifies and glorifies.

In expressing my gratification over the good work done thus far by the Institute, nothing is farther from my thoughts than the wish to suggest or imply that there is not still more, indeed, very much more, good work ahead, waiting to be done. In truth, my feeling is that it would be very difficult to set any limits to the development of the Institute and its capacity for the further advancement and realization of its aims and objects. There will be no dearth of good opportunities in many directions; and I am confident also that there will be no lack of initiative, interest and effort on the part of the active members whose self-sacrificing devotion has done so much, as I have already indicated, to raise the Institute to its present high plane of efficiency. As time goes on, with better resources and riper experience, the Institute will be able to undertake tasks of greater magnitude and solve problems presenting greater difficulties than would have been possible hitherto.

There is one thought suggested by the foregoing sketch of the Institute's career which deserves to be impressed upon the minds of all its members. It is this: wherever in the extensive fields of electrical theory and practise a man may happen to be stationed, either by his own choice or by circumstances, whether he be genius or plodder, whether he be ambitious or modest, and

regardless of his specialty, or whether he have any specialty at all, there is room for him in these fields, there is a place for him in the Institute, and work for him to do, and there are benefits and honors waiting for him there. The Institute needs him, and he needs the Institute. Each can complement the other and can add to the other's " stature " in many ways.

Although the evolution of the Institute has been rapid, it has been, fortunately, also healthy. It has acquired a strong impetus which should carry it along steadily to ever wider scope and more fruitful influence. There is no reason why the Institute should not continue indefinitely to grow, to expand, and to increase its power for doing good to our profession and for developing a true professional spirit in its members. I trust that you all join me heartily in the wish that the Institute's career may be long and brilliant and I hope sincerely that you will all continue to do your best to help make the wish come true.

The Social and Civic Evolution of the Engineer

The preceding sketch of the evolution and development of this Institute has made it apparent that the particular branch of the engineering profession for which it stands before the world has attained a place of great distinction and high honor in that community of initiates and adepts known as the domain of applied science and technology and sometimes called the engineering world.

We might be content and satisfied to rest on our honors in that world, if it gave scope to all our aptitudes, if there were in it opportunities for the cultivation of all our faculties and the development of all our talents, and for the realization of all our ideals and aspirations. Unfortunately, that world is, after all, only a sort of technological workshop of vast proportions and of complex character, wherein one may develop great abilities and talents, it is true, but which aims at one thing only, the performance of scientific and engineering tasks and " stunts " of great commercial interest and industrial value to the whole world. It is not suited for the development of what we are wont to term the higher, better and finer side of human nature, including those important constituents of human character, built up of moral, ethical and spiritual attributes and of sterling qualities of mind and heart, those elements of general culture, high-mindedness and refinement, which breed the feeling and nurture the respect for ideals, and which develop those charms and graces of manner

that raise certain individuals to higher planes, and entitle them to greater respect and consideration than the rest, in human society.

I know that I need not dwell on the desirability of this kind of development, for I am sure that you all concede its necessity and its benefits for all classes of humanity. We all see quickly enough the " mote " that is in the eye of humanity in general; unfortunately, we do not always see the " beam " that is in our own eye, so great is the difference between looking at a thing in the abstract and in the concrete. That is what leads me to mention and to insist upon a point of great moment, not only to ourselves but to the whole world. It is this: we are further behind than we ought to be, in certain phases of that higher development which has just been alluded to; we are merely *followers*, whereas we ought to be *leaders*. I will admit that this condition has not been worse,—in many respects, it has, indeed, been far better,—in our branch than in the other branches of the engineering profession; but, the fact that we have been merely a little less blind to our opportunities and our duties than have our colleagues, is not an adequate excuse for our own delinquency. It is, perhaps, an accusation, as showing that, although more awake, we were not more alert or active.

One of the important objects which I have in mind, in this portion of my address, is to bring to the attention of electrical engineers,—and, incidentally, to the attention of all other engineers or classes of engineers who are " in the same boat,"—the fact that the acquirement of what might be termed " technical adeptness and dexterity," either individually or collectively, by the members of a profession, and the resulting increase of technical knowledge, accumulation of experience and data, and development of engineering methods, do not constitute the *summum bonum* of our professional life, and do not represent our only ideals or the sole end and purpose of our efforts, either in an individual or in a cooperative sense.

In extending and improving our relations to each other, through our Institute, we have laid the foundations for the development of a great guild. Let us remember, however, that in this case we ourselves may not, indeed, we cannot, be the sole judges of greatness. In reality, it is not *self*-recognition, but recognition of a class by *all other classes*, that counts. This is a point to which engineers as a class have given altogether too little attention. They have been too self-conscious

and self-centered; and they have not paid enough attention to their relations to the outside world. They have neglected to cultivate, and, consequently, they lack, the "*guild-spirit*"—that force which makes for the increase of prestige, influence and power of the guild, and secures for it the greater respect and consideration of other guilds and classes. It is high time that engineers should appreciate the importance of "taking their place in the procession", in a social, civil, and civic sense. While, in a professional class, the prominence of *individuals* may depend only or mainly on professional technique and achievements, the prominence, reputation or *caste* of the *class* or *clan*, as a whole, depends mostly, perhaps wholly, on the professional spirit—the "*esprit de corps*",—and on the ability of the guild or class to hold its own with the other guilds and classes, on common grounds, in social, civic ,political and other life, in the outer world. The next point of interest is that we really have duties to perform and are entitled to benefits, in that outer world. Moreover, our neglect to preempt or to occupy the place that belongs to us there, is a serious handicap to the prestige or influence of our particular professional class, and places it in a condition of relative disparity, before the world, as compared with other professional classes,—such as those of law, medicine, the fine arts, etc., which assert their rights and utilize their opportunities systematically.

When people speak of the "upper crust" of society, they imply and recognize, tacitly, the existence of lower layers, strata or classes in human society. It were indeed idle to deny the existence of classes, orders or groups in human society, any more than in the rest of nature. It seems to be in nature's general program. We find classes in the infinitely great worlds of the astronomer, and we find them in the infinitely small worlds of the bacteriologist, and in that of the physicist; and we find them everywhere between these two extremes, in the animal, vegetable and mineral kingdoms. An interesting example of the stratification of life was noted by the Prince of Monaco in his deep sea explorations. He found that the ocean had upper and lower "layers", or "tiers" of inhabitants, with an indefinitely great number of intermediate layers; moreover each kind of life, indeed each species of fish or animalcule, has its place at a certain depth, where it is "at home", and above or below which it is "out of its element", and may be so uncomfortable or so handicapped that it cannot live.

In this entire system of stratification in the universe, the relative location of each layer may be the result of accident or circumstances, but it is always liable to change. In the case of the "layers" of human society, some important changes have been effected rather suddenly by *revolution*; but most of the changes occur by the slower and better process of *evolution*. The important principle of the "survival of the fittest" is always in operation here, for there is continual battling by contending forces, the weak being crushed or thrust aside by the strong. The social or civic level occupied by any class in human society is at the point of balance or equilibrium between its own efforts to rise to higher levels and the efforts of other classes to prevent them from rising in order to take their place.

It is my opinion, as it is also that of many of my colleagues who have given careful thought to the matter, that as a professional class, we are entitled to occupy a higher station and to receive greater consideration and respect than have been accorded us by the public. I will not deny that we have made considerable progress in the direction of social respectability and higher civil status. A recent review of the evolution of the engineer, in the London *Times*, contains the interesting statement that "Considerably less than a hundred years ago engineers in the navy took rank *next below carpenters*". It is most gratifying to realize that, in the present day, in all the navies of the world, the engineer is in the "officer" class and that, at least in our navy, many of them have attained the "Admiral" class.

In an address on "the position of the engineer in civic and social life" presented before an Austrian technical society in 1877*, one finds ample evidence that the civil and social status of the engineer were then far from satisfactory to the engineers themselves. There is lament over the fact that the older professional classes, which had hitherto divided the world amongst themselves, looked upon engineers as "upstarts" and "intruders". We may still be considered "intruders" by the lawyers and politicians who fill the positions that we engineers alone are qualified to fill properly on public service, public works, and

* "Die Stellung der Techniker in staatlichen und socialen Leben." Vortrag des Herrn Hofrathes M.M. Freiherr von Weber. Gehalten am 17 Feb. 1877. Wochenschrift des Oesterreischischen Ingenieur und Architekten Vereins. Vol. II, Feb. 1877, pp. 59-60. Mar. pp. 85-88. (To be found in A. I. E. E. Library, Mailloux collection).

other commissions dealing mostly with engineering questions; but, at least, we are no longer called such harsh names. So we have made some progress,—just enough, perhaps, to show how far we are still from where we ought to be. The following passage in the address is well worth quoting: "Only in rare, exceptional cases, do we see engineers, even in matters of specifically technical character, vested with the authority which gives the ultimate final decision; indeed, they are never in the majority in the deciding body". Further on, in the same address the statement is made that the final deciding power in matters of the kind already mentioned remains "in the hands of laymen, and that the preponderating majority is composed of amateurs generally having a pronounced legal 'tinge".

These remarks, thirty-seven years old, need practically no revision for presentation before an American engineering society today. They still report the conditions quite correctly. The author calls attention to the fact that the civil and social status of the engineer are higher in France and in England than in the German countries. The engineer has never been regarded and treated in the former countries as an " upstart " or an "intruder". Of the French engineer, the paper says that his education not only equips him with the necessary knowledge and preparation for the fulfillment of all his technical duties, but that it makes him, in general culture, good breeding and social tone, equal to members of all other social classes, and that he is, therefore, received and acknowledged as such without any opposition. This passage is interesting as evidence of the benefits attainable from the kind of training which supplements technical adeptness and dexterity by the development of personal character along intellectual, cultural, social, civic and ethical lines. The article concludes as follows:

" Let us set aside small jealousies and controversies, let us help uplift each other reciprocally and in that way also raise ourselves in the estimation of the world,—let us stand fast, shoulder to shoulder, in healthy solidarity against the outside influences which begrudge us equality of privilege with the older professional classes, and which strive to shut us out;—let us show, by our own discipline, that we are qualified to advise, to direct, to lead, in the highest capacities, and let us be on all occasions gentlemen in disposition and deportment.

"The conquest of that position in civil and social life for which we are striving and which belongs of right to us, on the strehgth of our knowledge and ability, will then result without fail."

It would be difficult to improve upon this good advice even at this later date. The fact that it is still so good shows that it is

till needed; for the millenium expected thirty-seven years ago s not yet quite here.

This plea for the proper recognition of engineers, as a professional lass, though based upon justice, is, in a sense, a selfish one, and, n urging it too strongly, we might expose ourselves to the charge f being actuated by a desire to gratify professional pride or anity. Fortunately, the real motive for the evolution of the ngineer in social and civic directions is one that is quite altruisic, for the benefits which will result from it for the engineering rofession will be trifling in comparison with the benefits to the ommunity, to the state, and to humanity in general. This may eem to be a broad statement, but it can be demonstrated.

We know that it is the engineer who, in the last hundred years, as effected the marvelous transformation in the material condiions of life and in the activity of communities which are starting to the historian, and which seem revolutionary to the supericial observer. The engineer has been too busy himself with he multifarious details of this gigantic task to note that what he has done has, in reality, reacted upon the whole tructure of civilization to an extent so great that profound alerations, if not entire remodeling and reconstruction, are needed o restore balance and equilibrium. Now, in this task of indusrial, social, economic, and political rearrangement and readustment, there is work for all classes; and, considering the highly echnical character of many of the problems involved, there is, especially, much work for which the training and experience of the ngineer are important if not indispensable qualifications. It s here that we need the voice and authority of the citizen who s also an engineer; but his place is taken and his authority assumed by the lawyer, the politician, the agitator and the utopist, each having as little useful technical knowledge as the other, but each presuming, nevertheless, to be an expert and an authority on questions that are beyond his ken. Let us note here a significant fact. Public opinion holds so much in consideration and has so much respect for the older professional classes,—law, medicine and theology,—that it would not tolerate the suggestion that the tribunals of justice should be administered by others than jurists, that questions of sanitation or hygiene should be decided by others than medical men, or that moral questions should be settled by others than clergymen When, however, it comes to questions involving scientific and engineering knowledge, public opinion seems to be satisfied to let them be discussed and settled by anybody whatever, preferably by *others* than engineers.

In older times, men could qualify for handling the problems of the civilization of their day without reference to technical science, as knowledge of law and religion was the fundamental requirement. A very little science went a long way in an age when sophistry and credulity were at a premium. As a result of the rapid progress of civilization along scientific lines, the importance of law and religion now sinks into insignificance, in comparison with science and technical knowledge as qualifications for dealing with the problems presented for solution. It does not require much thought or imagination to see that, in a society which is becoming daily more and more dependent upon science and engineering for its welfare and well-being, aye, for its very existence, there is more and more room and need for men of technical training at the helm in public affairs.

Some thirty years ago, the then president of these United States stated that "we are confronted by a condition, not a theory." Today, we have a different state of affairs. We are confronted by both conditions and theories, more especially by a great number and variety of theories, many of them of questionable soundness. This conglomerate condition is owing to the fact that we have too many "quacks", and not enough "doctors", in economics.

A sage of bygone times uttered the aphorism that there is no royal road to learning. Now, the world would not be so much disturbed or inconvenienced, if it were only royalty that aspired to acquire learning without having to pay the price. Unfortunately, that disposition has become epidemic at the present time, and what is still worse, the appearance is often accepted for the reality, so far as knowledge is concerned, more especially knowledge of civics and economics.

The framers of the constitution of the United States, in making a general statement that "all men are born free and equal," without making it clear that they meant freedom and equality in a civic and legal sense, rather than in a social or intellectual sense, left room for much misunderstanding and confusion. The untutored mind finds encouragement here for the notion that one man's opinion is as good as another's. He does not distinguish between the *right* to express an opinion, which is a matter of *law*, and the *value* and *authority* of that opinion, which are matters of *knowledge*. He forgets that while the right may not be disputed, the authority may be both disputed and denied. This self-constituted authority is a source of great

mischief, and it is, perhaps, the indirect cause of much of our social unrest or political inconsistencies and our economic disturbances. We are forced to realize and to admit that it puts a premium on ignorance.

The same process of reasoning that makes a man think he is an authority on all political questions makes him a partisan of direct legislation in its most radical forms. Instead of matters being improved, they are made worse. The reason can readily be seen. The burdens thrown upon the individual increase in proportion with the responsibilities which he assumes. In presuming to deal with and pass upon all civic, economic and political questions directly, instead of delegating them to representatives, he assumes implicitly the responsibility for informing himself about every matter, and getting at least as intelligent a grasp and comprehension of it as the representative is presumed to have. But here is precisely where the trouble arises. Many of the questions which he has undertaken to answer for himself, in doing away with representatives and proxies, and in becoming his own authority and guide, are questions involving and requiring more or less thought and study and inquiry into facts. It is work of a kind for which the average citizen has not the time or the inclination, even if he had the aptitude and the training. How can enlightened thought and opinion and rational action be realized under such circumstances? It seems natural to expect that most of the untutored and indifferent minds in the community will either jump at conclusions or arrive at them in a very superficial way, very much as one may try to get the news by merely reading the heavy headlines in a newspaper. In such a case, it is very important that the headlines should be set up by men who are intelligent, well informed and honest.

It is a momentous question which is asked when we inquire whither the untutored citizens, who constitute always such a large part of the whole mass, will turn to read these headlines, in their search for information; and the answer is far from reassuring. Some may read them in the sermon of a popular divine who is trying to fill the pews by observations on civics, economics, and other technical subjects of which he knows precious little. Others may read them in the speeches and harangues of agitators and fanatics, and no doubt many others find them in the corner saloons in the vaporings of some would-be sage, who, after finding inspiration at the bar, tries to imitate the sapient " Mr. Dooley " in solving the world's problems.

The sum total, the net result, of all this dilettantism is a condition wherein the blind are leading the blind. All this confusion, and all the blundering which it entails, could be and may be avoided by putting men and things back into their proper places. In seeking for causes, we are brought face to face with important facts. First, the present disregard for knowledge and authority among the masses, and the transition from a state or condition where a few privileged professional classes or sects were the only ones who presumed and were permitted to think and pronounce on public questions, to a state where all classes and, in fact, all individuals, assume the right and authority to do so, are undoubtedly consequences of long-continued abuse of authority by those who presumed to be the oracles of the people, and made believe that they knew all about things which, in reality, they did not know. Second, it is mainly lack of *scientific* knowledge that has caused the old-time oracles to fall from grace in the popular estimation. The days when scientific facts could be over-ridden and overshadowed by rhetoric and oratory, are passed. An ounce of technical knowledge is worth a ton of imagination, when it comes to handling scientific facts. The public lost confidence in its oracles because it found out, in time, that it is more important for statements to be *true* than to be merely *plausible*. Third, the public is not to blame for not having given to men of scientific training an opportunity to enlighten and advise it in matters of scientific fact and knowledge. The blame lies with the men of the scientific class themselves, for having allowed the public, as a body politic, to remain in ignorance of their very existence, to say nothing of their qualifications. It is unfortunately too true that the civil and social status of the professional engineer are far from being well defined in the mind of the general public. Indeed, there are indications that the scientific education, training, and experience of the professional engineer are very little understood and appreciated in the community. It is not strange, therefore, that the professional engineer should, by many, be regarded as merely a higher grade of skilled mechanic or artisan. To remedy this condition, steps should be taken to inaugurate and carry on a campaign of education of the public, with the object of acquainting it with the engineering class. It is time that engineers should assert themselves as a class and let the public see that they satisfy very substantially the requirements of an intellectual class, and one of more than

average grade, as well as of high civic character; that, as such, they are qualified to render important service to the community and to the state, and are entitled to recognition.

I wish, at this point, to make it plain and emphatic that the kinds of service and of recognition that I have in mind are not of political, but more of civic, social and ethical nature and character. I would be sorry to see any body of scientific men become a political force and acquire ambition for political power. It would be a lamentable waste and perversion of mental energy of high quality and development. In the beginning of this portion of my address I spoke of the development of the higher and better sides of human nature, and of the evolution of character along the lines of highmindedness and refinement, as the path over which man can attain to the highest civic and social planes. It is my opinion that not only the engineering class is capable of this higher development, but that it can serve as a strong leaven to promote that development in the community. In a word, I believe that, just as engineering has helped materially to improve physical conditions, so the engineering class can help materially to improve civic, ethical, economic and even moral conditions, in modern life. The education, the training and the experience of the engineer fit him especially for such a mission. He has to deal less with fiction and more with facts than most men of other intellectual classes. He learns early to understand and appreciate the value and the utility of scientific method and precision in his habits of thought and expression as well as in his work. He also learns early to distinguish between the classes of subjects with which he is competent to deal, and on which he may presume to speak authoritatively, and those classes of subjects which are not within his sphere or his scope, and in reference to which it would be absurd or even impertinent for him to pose as an authority. He knows that specialties in intellectual work arise from the limitations of individual mental aptitude and energy, and he is willing to concede that the specialist is likely to have more and better knowledge of a given subject than the amateur. He *might presume* to express an opinion on subjects involving *scientific* or *technical facts;* he *would hesitate* to express one on subjects involving scientific *hypotheses* or *theories;* and he *would be quite reticent* on subjects involving *metaphysical* considerations or speculations. The subjects of the class first mentioned may be presumed to be wholly within

his sphere; those of the next class are likely to be only partly so; and those of the last class are, as a rule, entirely outside of his sphere. The man who has been taught and trained to exercise such discrimination and discretion is qualified for sane, sound, rational, logical thinking; he is apt to be more careful and accurate in his statements; he usually says what he means and means what he says; and his opinions are bound to carry weight and receive consideration. They make an interesting contrast with those of the man who undertakes to cover all subjects with equal "fluency". It is well known that, as a rule, engineers and scientific men are more conservative in their statements than most men of the other educated and intellectual classes. This is the result of a better appreciation of the limitations of all human knowledge and of the importance of precision in thought and expression; it is, in a word, the result of better intellectual perspective and mental balance. These qualities are very valuable in the citizen, in the member of a community, as they are known to be in the engineer entrusted with important tasks. They only need to be known to be appreciated. They should enable the engineer to command the respect and receive the consideration of the general public, for they are bound to place him on a high civic plane, and make him an exemplar for the rest of the community.

That is the position to which I would like to see the engineering class attain. The other educated intellectual classes have had their "inning,"—their opportunity. Ours is yet to come. Deserve success and you shall command it. We must deserve and we shall obtain the confidence of the community; and when we secure it we must retain it, by continuing to deserve it. The engineering class can scarcely expect to reach the goal at one bound. It must expect to attain the higher position to which it is entitled among the thinking and intellectual classes by successive stages. It should delay no longer, however, in making a start and in taking the first steps.

I have not by any means exhausted the subject. There is a great deal more to be said, but I shall be content if I have aroused your attention to the importance of not neglecting our evolution along social and civic lines, and beyond the purely technical and professional lines which we have hitherto looked upon too much as being our final goal and the highest realization of our ideals.

I will offer, by way of conclusion, some thoughts summing up the situation, which, I hope, will receive your careful considera-

tion and will be borne in mind by you as having an important bearing upon the further evolution, in a civic and social sense, of the members of this Institute.

I. The Institute has made most satisfactory progress in the development of the activities and forces which conduce to its efficiency, which enhance its merits and enlarge its reputation as a forum for the discussion of questions and the study of problems in theoretical and applied electrical science. Its evolution in that sense and direction has been rapid and healthy; and it bids fair to continue to expand its sphere of usefulness.

II. The membership of the Institute, as a whole, has shown extraordinary devotion and loyalty to its interests, and a most edifying zeal in constant efforts to place it on a high plane among the engineering societies of the world.

III. The members of the Institute, as a class, have great respect for high professional ideals and ethics, and they have given enthusiastic and strong support to all movements and measures tending to their development in the Institute.

IV. The members of the Institute, in common with those in the other engineering societies in this country, have paid but little attention to the cultivation of professional ideals outside of the Institute.

V. As electrical men we have pre-empted and we hold a high position in that inner world which constitutes the engineering hierarchy. We have not attained the same high relative rank and position in the outer world, in civil and social life.

VI. In spite of the wonderful achievements which we have performed and the great contributions to the progress of civilization for which we deserve substantially the entire credit, we do not hold the place in the social scale that is commensurate with our professional attainments and our social qualifications.

VII. We have measured our weight and influence as a class by reference to what we think of each other, and by our mutual respect and consideration for each other, forgetting that our social position and status are determined wholly by what the outside world thinks of us, or the respect and consideration which it accords us, or which we demand and obtain from it.

VIII. The time has arrived when the members of the Institute should develop a class spirit through which a man in the engineering profession can attain to the place and high honor and consideration to which he is entitled among the other professional classes.

quality of work creating a popular demand in many classes of apparatus.

Electric air heating of spaces, upon which we will go into detail in this paper, is now rapidly coming into popular demand, its advantages, properly applied, making it a worthy competitor of other methods of air heating in marine engineering. The increased cost of operation over steam heat, although high in proportionate percentage, is not very great in actual dollars, in view of the low cost of generation of electric power aboard ships, and is further balanced by the convenience of locating the heat source where most efficient use of it can be made, the simplicity and low first cost of installation, especially where the air space to be heated is far from the boiler or engine room, the possibility of reliable automatic control of temperature, the low cost of repairs with little attention required, and the improved quality of service with freedom from leaks, noises, disagreeable odors and the other inherent objections to steam heating systems.

In some cases in the past, electric air heating systems have been failures, but usually these have been traced down as resulting either because the apparatus installed was the wrong design or insufficient for the conditions, the conditions such that an electric air heating system should never have been selected, or the particular electric heating system installed did not suit the conditions existing. In some places a small two- or three-lamp radiant heater was installed to heat a comparatively large space, the small radiator being selected probably because of high cost of power or because of the desire for appearances rather than for performance. It should be carefully considered before electric heating is installed whether the advantages of this system will overbalance the reduced cost of operation with steam, as unsatisfactory results in some past installations have proved hard handicaps to overcome, and have prevented installations that would have been very creditable. Care should be taken in selecting the design of heater and most appropriate method of installation, rather than placing appearances first, with a resultant sacrifice of efficiency, which appears to have been the practise in some past installations. As with electric cooking and industrial apparatus, electric air heating can compete with other systems only because of its adaptability, and this must be considered and made use of or the system will be found unsuccessful.

Heat is dissipated, as we know, by conduction, radiation and

convection. In considering electricity for space heating on shipboard we encounter, as a rule, metal bulkheads and decks which are good conductors of heat, and every effort should therefore be made to minimize conduction losses. The radiant and convector heaters, named from the manner in which the heat is furnished, have different conditions to meet.

The radiant heaters or electric radiators dissipate the heat principally by sending off radiant energy, raising the temperature of opaque bodies in its path, and as they respond instantly when turned on, have been found adaptable where a small amount of immediate warmth and intermittent use is required, such as in rooms not in general use, and where it is not desired that the temperature of the entire room be increased. Their efficiency for space heating on shipboard depends upon the material of the bulkheads and decks. As these are, as a rule, metal, which is a very good conductor of heat, a large part of the radiant energy is converted into heat upon striking the bulkheads and decks, is carried by conduction through the skin of the ship to the water and lost, or carried through the bulkheads and decks to the surrounding compartments and lost so far as the individual compartments are concerned. A feature observed in the radiant heater, worthy of mention, is the feeling of satisfaction when sitting in front of it (absent in a convector), caused by the cheerful glow present and, as has been stated by some authorities, the additional possibility of a physiological effect caused by the radiation of the higher frequency rays of infra-red, such as is experienced in sun baths.

Convectors heating the air in contact with resistance units, start convection currents which increase and maintain the temperature of the whole room. In space heating, where the surrounding walls are of metal, it has been seen that radiant heaters are inefficient in heating the air, and for this same reason in convectors the radiation losses should be kept down to a minimum. As the radiation increases as a function of the temperature, the temperature of the element should be kept low. Also it is better to heat a large volume of air a few degrees than a small volume of air a proportionately greater number of degrees. The former, instead of rising rapidly to the top of the room and there losing its heat through the metal deck above, will spread out more and warm by convection the air of the whole room.

To indicate the division of forms of heat dissipated by the

convector and radiant heaters the following was experimentally determined, using standard constructions:

	Radiant heater	Convector heater
Convected heat....	40 per cent	90 per cent
Radiated heat.....	55 per cent	5 per cent
Conducted heat....	5 per cent	5 per cent

The design of radiator appears to have settled on the glow-lamp type, although resistance wires operating at a red heat are coming into use. The location of the radiator is facing and within three or four feet from the person using it. In the standard designs of radiant heater, the glow lamp is the source of heat, and the

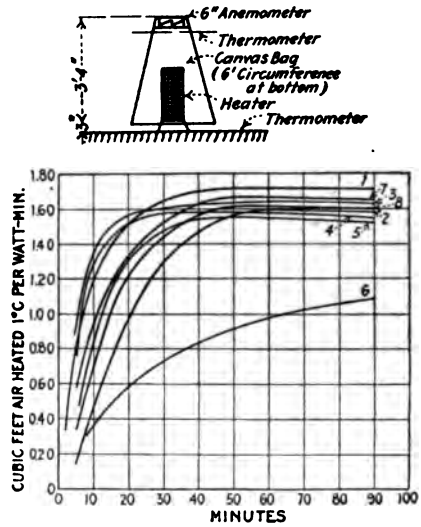

FIG. 1—AIR HEATED BY VERTICAL DRAFT.

commercial designs include two, three and four-lamp units, the lamps being either 250 or 500 watts each, as desired.

The design of convector heaters of the various manufacturers differs principally in the details of construction of the heating units. The formation of resistance units constructed of special resistance wire or ribbon, insulated and protected in various ways, and operating as close as practicable to a temperature best suited for the supply of convected heat, mounted in a manner to permit of efficient circulation of air, protected by a strong guard which does not restrict circulation and provided with a properly shaped deflector to give distribution of air desired, makes up this form

of heater. Practise has settled upon a long, low heater as preferable, which design, aided by a properly shaped deflector, permits of sending the heated air out from the floor, where better mixture and uniformity of temperature is obtained without the danger of concentration of high heat at the ceiling with a greatly reduced temperature lower down. A case has been cited of poorly installed heaters where the upper berths of staterooms have been surrounded by air at such a high temperature to make it uncomfortable, whereas a glass of water placed on the floor has been close to the freezing point.

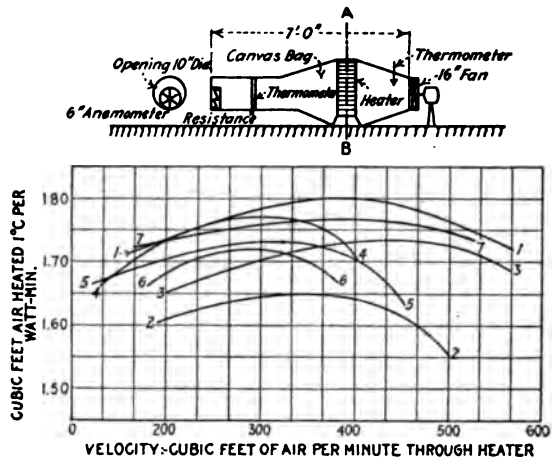

FIG. 2—AIR HEATED BY FORCED HORIZONTAL DRAFT.

No.	Input.	Cross-section A—B
1	3300 watts	169 sq. in.
2	2340 "	180 " "
3	3000 "	238 " "
4	1760 "	121 " "
5	2240 "	210 " "
6	1220 "	138 " "
7	3250 "	130 " "

The design of the heating element is influenced greatly by the desired standard of safety to be upheld, and this has brought out designs where the vibration and jar of marine service cannot cause disarrangement and possible arcing. Insulation of the supporting feet to prevent conduction of heat to the steel deck and bulkheads is looked after during installation and need not be considered in the design of the heater. The essential requirements of convector heaters are long life, maximum heat by convection available in a comparatively short time, a construction conveniently installed, safety, good appearance, and a flexible

design for different capacities desired in the various locations.

The operation of various designs of convector heaters is shown by the following curves obtained experimentally:

Fig. 1 shows the convected air by natural draft measured by anemometer and indicates the cubic feet of air heated one deg. cent. per watt-minute. This figure also contains a sketch showing the manner in which the convected air was measured.

Fig. 2 shows the air heated by forced horizontal draft, indicating in cubic feet of air heated one deg. cent. per watt-minute, and shows the variation with velocity of the operation obtained,

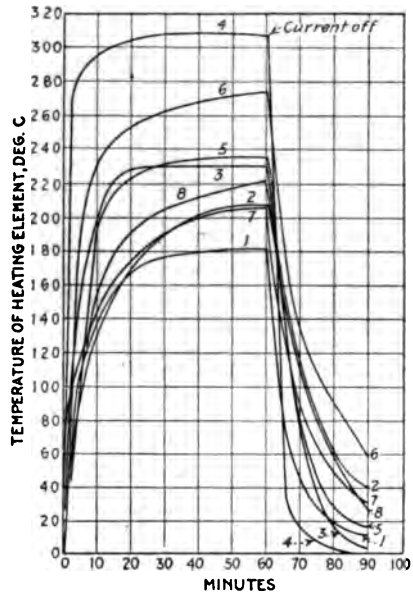

FIG. 3—CURRENT OFF AT END OF SIXTY MINUTES.

and is useful in considering such heaters for indirect heating, in which the heaters are placed in the ventilating ducts.

Fig. 3 shows the temperature rise of heating elements plotted against time for the respective heaters, and is useful in judging the performance of such heaters.

Fig. 4 shows the temperature distribution taken in a room 12 ft. by 21 ft. and 17 ft. high, with and without the use of deflectors of various shapes (see Fig. 11), and using one heater. Fig. 5 shows the temperature distribution in the same room as Fig. 4, only with the heater placed in the center of the room.

Fig. 6 shows the temperature distribution in a room 8 ft.

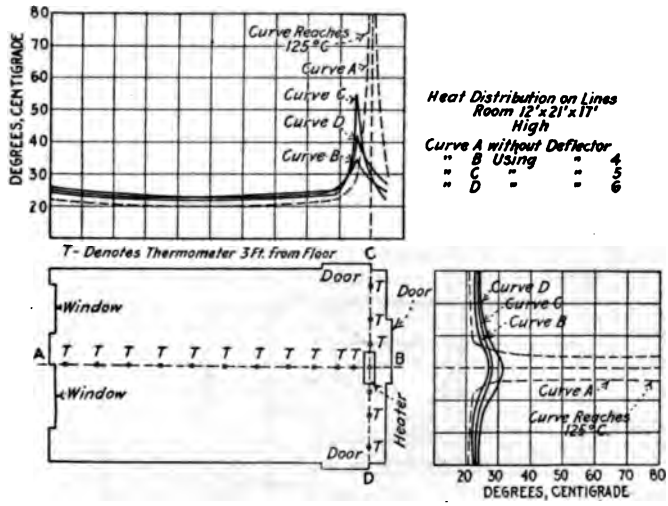
DEGREES, CENTIGRADE
Curve Reaches 125°C
Curve A
Curve C
Curve D
Curve B
Heat Distribution on Lines
Room 12'x21'x17' High
Curve A without Deflector
" B Using " 4
" C " " 5
" D " " 6
T- Denotes Thermometer 3 Ft. from Floor
Door
Window
Heater
DEGREES, CENTIGRADE

FIG 4

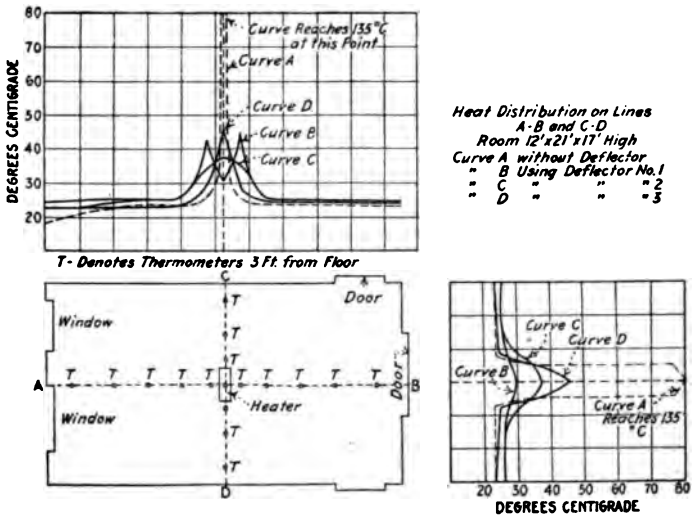
DEGREES CENTIGRADE
Curve Reaches 135°C at this Point
Curve A
Curve D
Curve B
Curve C
Heat Distribution on Lines
A-B and C-D
Room 12'x21'x17' High
Curve A without Deflector
" B Using Deflector No. 1
" C " " " 2
" D " " " 3
T- Denotes Thermometers 3 Ft. from Floor
Door
Window
Heater
DEGREES CENTIGRADE

FIG. 5

by 15 ft. and 9 1/2 ft. high with heater placed at the side of the room and using deflectors of various shapes.

Fig. 7 shows the dimensions of the living compartment in a submarine, and the results of tests of heating; Fig. 8 shows the

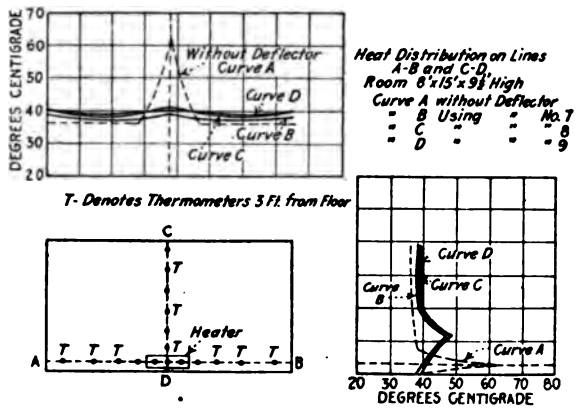

FIG. 6

dimensions of inner and outer staterooms and the results of tests of heating, and Fig. 9 shows comparative rise of inner and outer staterooms, using enclosed and bare resistance type heating elements.

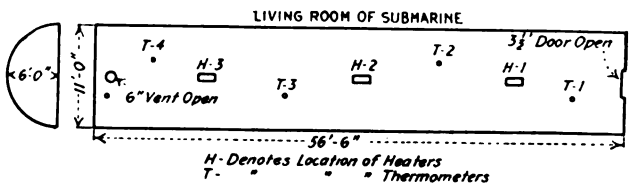

FIG. 7—HEATING TESTS ON SUBMARINE.

Temperatures in Centigrade

Hour	Total watts	Outside	1	2	3	4	Av.	Increase above outside
0	7600	8	16½	16½	17	16	16½	8½
2nd	7600	8	18	18	20	17½	18½	10½
3rd	7600	8	18	18	20	17½	18½	10½
6th	7900	8	20½	20½	22	20	20½	12½

NOTE: Deflector No. 3 placed on 2 heaters at end of 3rd hour.

Fig. 10 gives a comparison between glow and convector types of heater as regards convected heat given off, and Fig. 11 shows the types and arrangement of deflectors used in obtaining the data for the curves herewith.

From results of tests conducted during this investigation the following general results were obtained:

(1) For each 1000 cubic feet of space, 1500 watts input is required to maintain the temperature of air space of staterooms at 70 deg. fahr., based on the heater being installed in the center of the space, having an average height of 7.5 ft., and also based on replacing the entire space of air at outside temperature of 32 deg. fahr. every quarter of an hour.

(2) Where heaters are placed as in paragraph (1), but

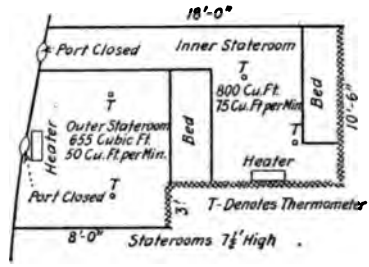

FIG. 8—HEATING TESTS IN STATEROOMS.

Hour	Watts	Position of heater	Type of deflector	Temperature in Centigrade: Outside	Passage	Room average
			Inner Stateroom			
2nd	2760	Center	None	10	20	22
3rd	2760	"	"	10	20	22½
5th	2360	"	No. 3	9	20	27½
3rd	2260	Side	None	8	20	24
4th	2260	"	"	8½	21	24½
7th	2530	"	No. 5	8	21	28
			Outer Stateroom			
2nd	2040	Center	None	10	20	21
3rd	2040	"	"	10	20	21½
5th	1740	"	No. 3	9½	20	27
3rd	1650	Side	None	8	20	25½
4th	1650	"	"	8½	21	25½
7th	1840	"	No. 5	8	21	29

installed with deflector of design No. 2, the input should be 1200 watts for 1000 cubic feet space.

(3) Where heaters are placed close to a bulkhead, without a deflector, the input should be 1300 watts.

(4) Where heaters are placed close up to a bulkhead, and a deflector of design No. 4 is used, the input should be 1100 watts.

(5) Where the space exceeds 20 ft. in either length or width, more than one heater should be selected.

It has been brought out by Dr. Langmuir that the heat loss by convection in small wires is nearly independent of the diameter,

and it has been found in electric convectors that with the units at the same temperature, the amount of convected heat given off per watt input, increases when the diameter of the unit is decreased. However, as the unit must be of substantial con-

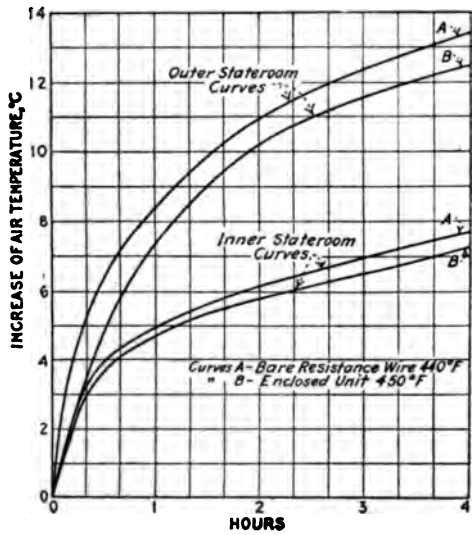

FIG. 9—COMPARATIVE TEMPERATURE RISE IN STATEROOMS

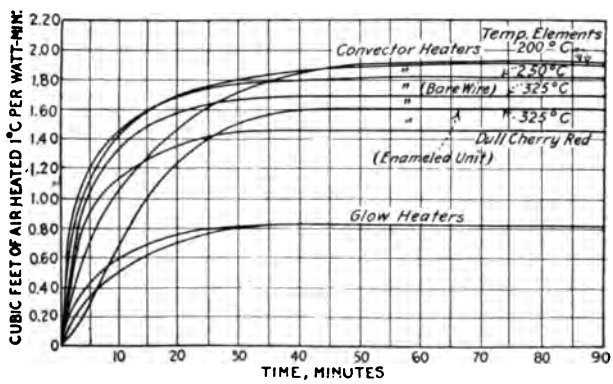

FIG. 10—AIR HEATED BY NATURAL VERTICAL DRAFT—COMPARISON BETWEEN GLOW AND CONVECTOR HEAT.

struction, the use of small diameter units is precluded, to some extent, by other considerations.

Convectors should, where possible, be fixed in or near the center of the room, but this is, as a rule, impracticable and it becomes

necessary to secure them near a bulkhead. The effect of their position on the heating of a room is shown in Figs. 4, 5 and 6. When mounted near a bulkhead, the heaters should be heat-insulated fron the bulkhead and the back of the deflector should also be heat-insulated so that the losses through the walls can be kept low.

The investigation, the results of which are shown in preceding paragraphs, was conducted in order that the advantages of the best features of design and installation might be made use of to bring up the efficiency of the installation and minimize the ob-

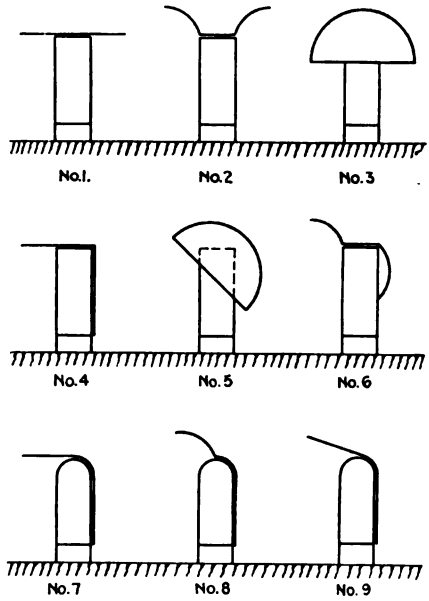

FIG. 11—DEFLECTORS USED.
Material No. 28 B. & S. gage sheet iron.

jection to the cost of electric air heating systems. The system of heating of spaces on shipboard which is now receiving most attention is a combination of steam and electric. Air for supply to spaces aboard ship is drawn in, by blowers from outside on the upper deck, through steam coils known as a thermo tank, and delivered to the spaces at about 50 deg. fahr. In each stateroom an electric convector heater is installed by which any additional increase in temperature is available to the occupant, and such temperature may be maintained by an automatic regulator thermostat installed in the convector circuit. This very conveniently re-

out the tests more carefully, and for longer periods of time, to confirm this conclusion.

The general conclusions as to the adaptability of electric heaters in marine service are encouraging. The modern ship is an industrial power installation of the most compact type, and the improvement in load factor by a mixed heating and cooking load would make an investigation of additional interest.

Alfred E. Waller: The curves shown in this paper, so far as rapidity of obtaining heat is concerned, appear to indicate a certain amount of advantage in favor of the open wire coil heater. It is my belief, however, that the advantages obtained by using heaters with entirely protected coils more than offset the slight advantage gained in the quick heating of the open coil type.

Enclosed or protected resistances can be made to reach their maximum temperature almost, if not quite, as quickly as the open type, and the extra time required to reach this maximum temperature is relatively unimportant if we compare it with the total time the heater is in use.

Suppose, for instance, that an open coil heater emits heat at the required rate twenty minutes after the switch is closed, and an enclosed heater takes forty minutes under the same conditions. This is an extreme case, and does not by any means represent the best performance to be obtained with the enclosed type heater. Under these circumstances, if the heaters are run for twelve hours, one takes 1/36 and the other 1/18th of the total elapsed time to reach full heat.

Disregarding this question of initial heating until it can be further investigated, I recommend the use of heaters with fully enclosed or protected resistors, for the following reasons:

Heaters are designed with two main objects in view—the first, that they shall give off heat, and the second, that they shall continue to operate for the maximum possible length of time with the minimum of repairs and replacements of units. It seems therefore very necessary that the resistance element should be protected in some manner, so that the moisture encountered in marine service shall not come in contact with the resistance.

A protecting layer of insulating and heat-conducting material, placed around the resistance wire or ribbon used in a heater, may be so arranged that it will not only exclude moisture, but will also protect the resistance material against chemical depreciation or mechanical injury of any kind. The support given the resistance element throughout its entire length is another advantage.

The possibility of short circuits, grounds, and dropping of molten metal which may occur as a result of burn-out in an open coil resistance will be readily appreciated. In a properly designed unit of the enclosed type, this danger is entirely eliminated.

One objection which has been urged against the enclosed type is that the weight is greater than that of an open type resistance.

This is not necessarily true, for the enclosed type resistance unit may be made considerably smaller than the open type, even if the total area of each heating unit is the same. This is because open coil units must be made of wire much heavier than is necessary in constructing an enclosed type unit, in order that the resistance may be mechanically strong enough to stand up in service.

I believe there is room for considerable investigation along one or two lines. One of these is whether it is not possible to use an enclosed type resistance run at a relatively high temperature, and to surround this by baffle plates or deflectors, which will cut off the radiant heat referred to by the authors, and at the same time permit a compact, mechanically strong and adequately protected unit to be used.

Another point which occurs to me, is the outside paint or covering on the heater. Dr. Carl Hering has published a number of discussions in the last few years on the general subject of surface resistance to thermal flows. These articles emphasize the influence which the outside surface of a body has upon the convection and radiation of heat. Related to the same subject is a paper presented by Dr. Irving Langmuir before the American Electrochemical Society. In this he discussed the effect of a polished silver surface.

Another interesting example is a foundry of which I have heard, in which the workmen whitewashed the outside of the furnaces, because they were then able to work near them in more comfort. The whitewash apparently had the effect of producing a high contact resistance between the furnace and the surrounding air, and the heat loss by radiation from the outside of the furnace was reduced.

The temperature of the outside of this furnace was found to be several degrees higher after the whitewash had been applied, this being the result of stopping part of the emission of heat by radiation.

It is an interesting paradox, if we consider two furnaces of exactly the same type and size, operating at the same internal temperature, one whitewashed and the other not whitewashed. In this case, the furnace with the hotter exterior would be operated with the greater efficiency—a condition which appears unreasonable until the attendant conditions are known.

Charles D. Knight: There are a few points I would like to draw attention to in connection with the paper. First, it is my opinion that the convector type of heater is much more efficient than the radiant. I also agree with the authors that it is better to heat a large volume of air to a few degrees than a small volume to a proportionately greater number of degrees. This is probably more important in the heating of houses than battleships, due to the fact that curtains, draperies and other material may come in contact with the heater.

The authors very clearly defined the amount of power required to heat a room of a certain area, and this brings up the

question of the very large gap that the power companies have to cover in reducing the price of power per kilowatt-hour. The authors have said that power can be generated in battleships for one cent per kw-hr., and I have no doubt but what the power companies can also do this, but when you consider the maintenance of the lines, and the expense of running them throughout the city over great distances, the cost becomes much greater.

When we figure out an ordinary size house, we will say with 20,000 cu. ft. of volume, we know that with hot air, hot water or steam it can be heated for $125 a year. Some rough figures, which I have made, will show that electricity at 5 cents per kw-hr. would cost very nearly $2,000 a year, and at 1 cent per kw-hr. about $400. It can readily be seen what the electrical engineer has to do in the matter of reducing cost of power to meet the competition which I have just mentioned.

D. B. Rushmore: I think it would be interesting, as this paper goes on record and is necessarily read by people outside of the Institute, if the authors will put in a little explanatory clause, as to how they calculate the cost of power on the battleship. That is a matter which is often misleading to people who are not familiar with the subject. I presume they leave out the original investment in the boilers and tanks, which would occur in a central power station. As an illustration, a man can raise coffee in Brazil, we will say, for five cents a pound, just as he can generate a kilowatt-hour, under certain conditions, we will say, for one cent, but the expense of getting the coffee into the hands of the consumer is what runs up the cost. It must be taken to the ship, brought to the country of consumption in the ship, then transferred to the wholesale houses, thence to the distributors, thence to the grocers, thence into the pantry at your home, which will probably cost about 35 cents per lb., and, therefore, you pay 40 cents per lb. for the coffee. That is the rough figure, but the figure on the cost of power is so disturbing to public utility companies just now, that unless an explanation is put in as to how this cost on the battleship is arrived at, the statement is apt to cause some misconception.

F. C. Caldwell: There is a very general idea that the radiant heater is too expensive in current consumption for common use in residences. The radiant projection of the heat directly upon the body to be warmed, however, makes it much more economical than is ordinarily supposed, and it is a great source of comfort as an auxiliary means of heating in a room where persons only occasionally gather. The absence of time lag in the effect obtained from a radiant heater adds greatly to its usefulness for such occasional duty.

We have found during the past year that the most appreciated electrical appliance in our household is an electrically heated blanket, or quilt, which consists of an ordinary bed-size quilt with a resistance wire woven all through it. This makes all the difference between comfort and pretty strenuous existence in outdoor sleeping, when the temperature is about zero. It

is something which should be used and appreciated much more than it is at the present time.

D. M. Mahood: I will take up the important points in the order in which they were presented, and comment on them as briefly as possible. Mr. Hadaway called attention to the variation in the curves in Fig. 9. We intended in that curve to show only the comparison between the bare resistor and the enclosed unit, and not a comparison of the heating of the inner and outer staterooms.

Mr. Waller commented on the comparison between the open and closed type of unit. Where it is possible to install an open rheostat without danger on a battleship, we can, of course, install a bare unit, but we would not think, for instance, of putting an open type of unit into a powder magazine or anything like that. It is the old story of adaptability—you must consider the conditions of the installation as well as the design of the material you are installing.

Mr. Knight and Mr. Rushmore both commented on the cost of power. The cost of ship-generated power, 1 cent per kw-hr., is the actual cost of generation. It does not take into consideration the cost of installation, depreciation, or the investment. In marine service, we have conditions very different from those prevailing in land work. We have the boilers, of necessity, for the purpose of propelling the ship, and the additional load for electric heating is small on the generating plant, and fits in very nicely with the other loads, the power and the lighting, and really, as a matter of fact, runs the boilers at a slightly better efficiency load.

Mr. Caldwell made reference to the radiant heater. The radiant heater is worked at a disadvantage in marine work, because we have the metal bulkheads which conduct off the heat received from the radiator. It is necessary, in order to use a radiant heater, to step right in front of it to get the effect of the heater. It is found that practically but little of the heat is sent off as convected heat, after it strikes the bulkhead—it is practically all conducted off. That brings us down to the convector type. The conditions on land are different. You have the wooden walls, which are poorer conductors, and for that reason the radiant heater has a greater field than it has in marine work.

H. A. Hornor: The battleship situation is one of metal bulkheads solely. In the merchant marine service, where you have the wooden bulkhead, and particularly out on the western coast, the conditions are more satisfactory. We recently built a ship to which we applied the radiant heaters. Practically every stateroom had a radiant heater of the three-unit type, and all public places had special fireplaces of the radiant heater type. It was a pretty effect, and the operation was very satisfactory. The conditions on the Pacific Coast are that the temperature changes are not violent, and the application of the heating apparatus to a passenger steamer was a good one.

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THE ELECTRICALLY DRIVEN GYROSCOPE IN MARINE WORK

BY H. C. FORD

ABSTRACT OF PAPER

The gyroscope when continuously driven by electric power may be used for various purposes, many of its applications having especial value in marine work.

Small gyroscopes are used to establish base lines for the measurement or control of angular motion. The gyro-compass makes use of the earth's daily rotation and consequent changing direction of gravity to secure a directive force a hundredfold greater and more accurate than that of the magnetic compass.

A general description is given of the gyro-compass as adopted by the United States Navy for use on all the battleships and submarine vessels. Many electrical and mechanical devices have been developed to perform the various functions whereby an instrument of great precision has been secured.

Large gyroscopes are made which are capable of counteracting enormous wave forces and completely stabilizing any ship against rolling in the heaviest seas.

UNTIL a few years ago the gyroscope was little known or heard of except as a child's toy, although as far back as 1852 its action was investigated by the French scientist Foucault, who published the results of his experiments in which he laid down very clearly the laws of its action.

His first law states that any gyro or spinning body possessed of three degrees of freedom, *i.e.*, free to rotate about a spinning axis and two other axes all normal to each other, will tend to maintain its axis of spinning fixed in space and may therefore be used to show the rotation of the earth. He also demonstrated that when a gyro was given a forced motion of rotation about one of the axes, the gyro would powerfully resist such force while at the same time tending to place its axis of spin in line with or parallel to the axis of the impressed force. This motion which takes place about an axis at right angles to that of the impressed force is known as gyroscopic precession and always occurs in such a manner as to bring the direction of spinning the same as that of the impressed force, and by the shortest path. In

other words, if the spinning axis were horizontal and the axis of precession vertical, then the gyro, by virtue of the impressed force of the earth's rotation, would turn about in aximuth and place its axis of spin as far as possible in line with the earth's axis (*i.e.* upon the meridian) after the manner of a true compass. This strange resisting force with its unexpected motion of precession at a different angle and apparently unrelated to the impressed force, is in reality a simple and logical result of the inertia of the moving mass. Its explanation is well known and follows directly the application of Newton's laws.

It is not, however, the purpose of the writer to go into abstruse theoretical considerations. Suffice it to say that the law of precession explains fully the observed facts with regard to parallelism of the two axes, and is well illustrated in the accompanying figures, Nos. 1, 2 and 3, which show an ordinary gyroscopic top *A* mounted in a Cardan ring *B* by pivots *a*, the outer pivots *b* being supported upon a fork *C* rigidly mounted upon the base *D*. Suppose the wheel with all parts symmetrical, as in Fig. 1, is rotating clockwise, viewed from above, and we grasp the Cardan ring and depress it on axis *b* to position shown in Fig. 2. First it will be found that the Cardan ring is possessed of a quite remarkable amount of rigidity and opposes the forces tending to tilt it. However, as these forces are applied, and though the ring *B* is moved only slightly, yet the gyroscope is seen to immediately swing vigorously through a wide angle upon its axis *a* to the position also shown in Fig. 2. Upon lifting the Cardan ring the gyro will again be seen to swing vigorously in the opposite direction until arrested by the stop as shown in Fig. 3.

For nearly half a century after Foucault had demonstrated its action, the gyroscope was put to no practical use. The late American author and scientist Hopkins, whose writings were published for many years in the *Scientific American*, was the first to drive a gyroscope electrically. He was able to enlarge on Foucault's experiments and obtain much more persistent results with his continuously driven wheel.

The first serious application of the gyroscope in engineering work was by Obrey, an Austrian naval officer, who made use of the gyroscope to steer torpedoes. About 1903 Dr. Schlick, a German engineer, proposed the use of the gyroscope for stabilizing ships against rolling and built a number of experimental plants which were tried out with some little success. At about

the same time Lewis Brennan brought general public attention to the gyroscope by his announcement of a railroad car that would maintain its equilibrium on a single rail. A car of this type was exhibited in this country in 1910 and the subject of monorail traction was much discussed in the press at the time in connection with the possibilities for high speeds which were claimed for this invention.

Practically all of the serious applications of the gyroscope, and by far the most important of its uses at the present time, have developed in marine work. These are the steering of torpedoes, the use as a compass and the use for stabilizing and controlling the motions of ships, the last two of which will be discussed more fully.

Several minor applications have been made, such as (1) stabilizing of various instruments, telescopes, etc., against oscillations when mounted on a rolling ship; (2) stabilizing of a pendulum carrying a pen for recording the angles of roll and pitch of a ship; and, (3) stabilizing a horizontal mirror for use as an artificial horizon in taking observations at sea. Some very valuable results have been accomplished along these lines, but the limits of the present paper will not permit of more than a brief mention. Various attempts have also been made to stabilize a body with three degrees of freedom for use in the direct determination of latitude and longitude, but so far as is known, without practical success.

Fig. 4 shows a form of telescope used on board ship for obtaining bearings of distant objects, which has been stabilized by means of gyroscopes so that it is entirely unaffected by motions of the ship in any direction.

Fig. 5 shows one of several types of apparatus which have been constructed for recording the rolling and pitching motion of a ship upon a moving sheet. In the instrument here shown, records of the azimuth as well as various time markings are made simultaneously upon the same record sheet.

Errors are frequently introduced in navigation when measuring the altitude of a heavenly body above a false horizon caused by mist or by the mirage effect of the heated air on a tropical sea. Very frequent observations of the sun or heavenly bodies could be taken were it not that the horizon is obscured by low-lying banks of fog, or darkness.

Fig. 6 illustrates a gyroscopic artificial horizon which provides a means for eliminating these errors in observation and

makes it possible to measure accurately the altitude of any heavenly body that can be seen, whether or not the horizon is obscured.

The automobile torpedo, as is well known, depends upon a gyro steering gear for its directive power and would in fact be utterly ineffective for its purpose without such a device. The importance of the torpedo in warfare is of course recognized, so that the great value of this application of the gyro needs no further comment.

The gyro compass shown in Fig. 7 is now being installed upon all of the battleships and submarines of the United States Navy, where it is depended upon absolutely for use under battle conditions where the magnetic compass could not possibly be employed, due to the large masses of magnetic material constantly being moved about in proximity to the compass. As an instrument of navigation the gyro compass has also proved of great accuracy and value in enabling the ship to be held steadily upon its course irrespective of wind, sky or sea. The foreign navies are also rapidly adopting the gyro compass and it seems certain that its use on all of the larger steamships and ocean liners will be found in a few years when its great advantages have become more widely known.

The very high development of the gyro compass during the past few years has been largely due to the efforts of a pioneer in the electrical art, Mr. Elmer A. Sperry, whose long and interesting experience with gyroscopic phenomona and belief in their engineering possibilities led him to devote practically all of his time to its development.

It has been the privilege of the writer to be associated with Mr. Sperry for several years past in this work, during which time a plant has been organized and equipped for the design and manufacture of many forms of gyroscopic apparatus.

A number of workers abroad have also been laboring with great persistence and some degree of success to solve the many physical problems involved in translating the idea of Foucault into concrete terms of steel and bronze which will function under the extremely severe conditions on shipboard.

The nature of the problem is indicated when one realizes that the gyro compass is so sensitive that it responds instantly and with the highest degree of accuracy to the very slowly impressed angular motion in space about the earth's axis four thousand miles distant, while at the same time it remains indifferent

FIG. 1 [FORD]

Cardan-Mounted Gyro for Demonstrating Gyroscopic Precession.

FIG. 2 [FORD]

Precession Carrying the Upper End of Shaft to the Left by Tilting the Cardan Ring Downwardly.

FIG. 3 [FORD]

Precession Carrying the Upper End of Shaft to the Right by Tilting the Cardan Ring Upwardly.

FIG. 4 [FORD]

Telescope Stabilized by Gyros.

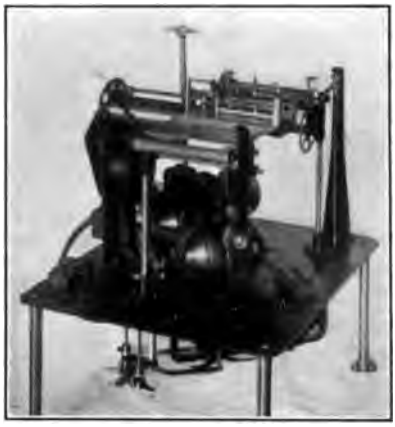

FIG. 5 [FORD]

Instrument for Recording the Rolling, Pitching and Yawing of Vessels.

FIG. 6 [FORD]
Gyroscopic Artificial Horizon.

FIG. 7 [FORD]
Master Compass with Covers Removed.

FIG. 8 [FORD]
Model for Demonstrating the Action of the Gyro Compass.

FIG. 10 [FORD]
Complete Equipment for a Gyro Compass Installation on a Battleship.

to the angular movements of the ship several hundred times greater in intensity.

In view of the extensive use of the gyro compass and the nature of the problems involved in its development, it may be of interest to look into the theory of its action somewhat briefly and then to note some of the many special construction details and various electrical devices employed in this highly organized instrument.

Fig. 8 shows a small device which may be used to demonstrate the action of precession in the gyro compass. In this device we have a small disk marked with the cardinal points to represent a compass card and mounted upon a ring swiveled to rotate on a vertical axis within a hand-supporting frame. The ring carries a wheel which spins upon a horizontal axis fixed in the ring parallel to the NS line of the compass card. If the device is held extended in the hand while the demonstrator turns slowly on his heel toward the left, we may consider his body as the axis of an imaginary earth and his head as the virtual north pole, since his rotation would always be easterly.

If the device is extended with the axis of the card perpendicular to the body at the waist line, the compass may be considered as located approximately at the equator. If held opposite the shoulder, with the axis of the compass card or handle making an angle of 45 deg. with the body, the compass would be represented in operation at latitude 45 deg. north.

Now when the wheel has been made to spin in a clockwise direction viewed from the south side of the card, if the device is carried about in the hand as above, the card will immediately orientate or turn on its axis to bring the north side toward the virtual north pole.

If the demonstrator should reverse his direction of rotation and turn toward the right, which would now represent east, we should have to consider that the north pole had been shifted to his feet, and if the little model is a true compass it should also reverse its direction and point to the new pole. This is what actually occurs, for the gyro compass not only holds to the meridian when placed thereon, but is actually possessed of a powerful north-seeking tendency many times greater than that of the magnetic needle.

The above demonstrates the elementary action of the gyro compass on an imaginary earth, the length of whose day is about twenty-four seconds. Under such conditions this little compass is ideal in its simplicity.

When, however, we are considering an instrument of precision, for actual use on a ship rolling, pitching and yawing in a heavy sea, or maneuvering at various speeds in every possible direction, the matter of picking out this demonstrator who will keep his body parallel to the earth's axis under such conditions and rescue a struggling directive force from the waves, is a somewhat larger contract.

As a matter of fact, many and serious are the mechanical and theoretical problems which had to be solved in producing a practical compass for navigation. For example, when mounted on a ship steaming rapidly north, say, the gyro axis does not point true north, but has a certain deflection, for the reason that the actual motion in space is no longer due easterly, but is about a resultant axis somewhat to the westward of the earth's axis. The amount of this deflection, which is a variable, depending upon the speed, course and latitude of the ship, has been exactly determined for all conditions.

In the Sperry compass a device is employed which corrects for the above factors and automatically introduces this correction into the compass readings, which are therefore always made accurately upon the meridian. Other special mechanical devices are employed for the following purposes, among others:

a. To provide a substantial mounting for the gyro element with the highest degree of sensitiveness.

b. To damp oscillations in azimuth.

c. To compensate various acceleration pressures.

d. To prevent errors caused by retardation of the wheel.

e. To set the compass quickly on the meridian even when the direction is unknown.

f. To prevent errors due to persistent oscillations in certain oblique planes.

g. To admit of determining the speed of the wheel by observation.

Space will not permit of a further study of the many theoretical problems involved nor of a detailed description of all the mechanical devices employed in this solution.

The general arrangement of parts constituting the Sperry gyro compass is shown in Fig. 9, which for greater clearness in illustrating the various functions has been simplified by the omission of electrical circuits and minor details.

The gyroscope wheel is mounted to rotate on a horizontal shaft A within the casing B, which is pivoted on the horizontal

axis C through its center of gravity and carried by the frame or vertical ring D.

The ring D is suspended by a torsionless strand E and guided by bearings F and F' to allow a free oscillation of limited amount about its vertical axis within the frame or "phantom" G, so called because of its characteristic action as a "shadow" in following up each motion of the ring D. The phantom G has a hollow stem H to which the strand E is attached at its upper end, and the stem forms a journal for rotation in azimuth with respect to the supporting base frame J.

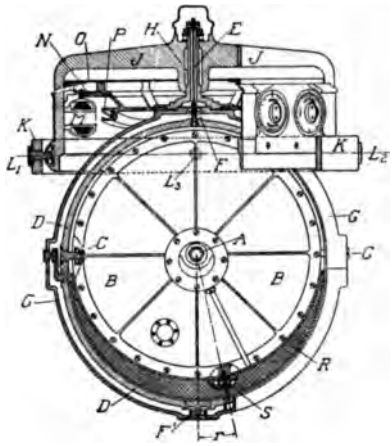

FIG. 9—METHOD OF MOUNTING THE DIRECTIVE ELEMENT

The frame J is mounted to swing in the binnacle by the usual Cardan suspension, consisting of the ring K and suitable bearings $L1$ $L2$, $L3$ and $L4$, the last not shown.

The frame J carries a "follow-up" motor M, driving a master gear N, forming a rigid part of the phantom G, whereby the latter is positively driven in azimuth to respond to any movement of ring D.

The ring D, which with the wheel casing is termed the "element," carries a pair of electrical contacts in the form of trolley wheels, which cooperate with stationary contacts mounted upon the phantom G for the purpose of controlling the follow-up motor M, the electrical connections not being shown in the figure.

The power-driven phantom G is thus automatically controlled so as to respond instantly to all movements of the sensitive element, and in fact to all relative movement in azimuth between the ship and the gyro.

This characteristic of the phantom enables it to be used for various important functions, namely, to carry the scale or card O and a cam P forming part of the automatic correcting device. The power drive is also utilized in operating the transmitter for the repeater instruments, and in overcoming friction of the slip rings needed to carry current to the gyro.

Since the phantom G, though at all times rigidly anchored to the binnacle, stands in practically constant relation to the sensitive element as regards motion about the vertical axis, but is nevertheless entirely separate therefrom, it serves as an anchorage for producing stresses to restrain and correct the movements of the sensitive element. This is accomplished by means of a yielding connection between the phantom G and the gyro case B, in the form of a pendulum or bail R, supported by and forming a part of the phantom. The point of attachment S to the gyro casing is located in a certain position eccentric to both the vertical and horizontal axes of the gyro. By this means several most important results are obtained, including positive orientation and the prevention of oscillation.

The complete electrical equipment of the compass system which will now be considered comprises:

1. A voltage regulator of special design.
2. A three-phase a-c. generating set.
3. A 20-volt d-c. generating set.
4. A d-c. emergency service.
5. An alarm system.
6. An automatic control and protective system.
7. Specially designed controlling switches.
8. The gyro motor.
9. A servo-motor or follow-up system.
10. A secondary transmitting and receiving system.

Fig. 10 illustrates the various parts of the Sperry gyro compass system for use on a battleship. The master compass and controlling apparatus are installed in a protected portion of the ship behind heavy armor. The repeater compasses are mounted at various points about the ship at the different steering stations. On a battleship, for instance, repeaters are supplied at the main steering platform, others on the bridge for taking bearings, one in the conning tower for steering during battle, one in the steering engine room at the stern of the ship, and in some cases one or more additional repeaters in ships provided with additional steering stations.

The compass is also used in connection with various other instruments for obtaining and recording various data.

A most important use of the gyro compass is on submarine boats which derive their power, when submerged, from storage batteries, the voltage of which varies at times from as high as 160 volts down to 100 volts at the end of a long run. An economical form of voltage regulator has been devised for such service.

FIG. 11 [FORD]

Rotor and Stator of the Gyro Motor.

FIG. 13 [FORD]

Automatic Correction Dials, Setting 15 knots, 40 deg. North Latitude.

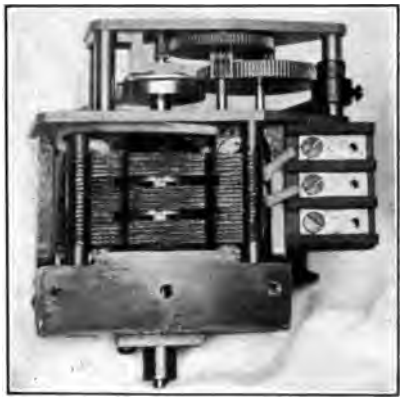

FIG. 14 [FORD]

Azimuth Motor for Driving the Phantom.

FIG. 12 [FORD]

Power-Driven Frame or "Phantom" arranged to Shield the Directive Element from External Disturbances.

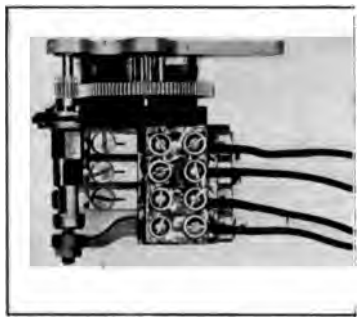

FIG. 15 [FORD]

Transmitter for Operating Secondary or Repeater Compasses

FIG. 18 [FORD]

The Precession Engine.

FIG. 17 [FORD]

One of the Two Large Gyros of the U. S. S. *Worden* while under Preliminary Tests at the Navy Yard, New York.

The problem of accelerating and driving the heavy balance wheel (the compass wheel weighs about 45 lb. or 20.4 kg.) at a velocity of about 8600 rev. per min. required the design of a special form of generator, three-phase current at 90 volts being used. The characteristics of the generator allow of the wheel being thrown directly upon the line and brought up to full speed automatically in about thirty minutes without attention on the part of the operator and without the use of excessive current. This machine, shown in the background of Fig. 10, has a capacity of three amperes per phase, but is ordinarily run under a load of 0.9 amperes.

The 20-volt d-c. dynamotor also shown in Fig. 10 is used in supplying energy to the servo-motor follow-up system and for operating the secondary or repeater compass system. No special features of design were necessary other than to meet the usual requirements on shipboard as to commutation, rating, accessibility, etc. In battleship equipments, both of the above generating units are ordinarily supplied in duplicate.

An emergency direct-current service is provided by the employment of a 20-volt storage battery which is kept floating upon the line at all times. This provides energy for operating the follow-up system of the compass whenever the ship's service has failed. During such times the gyro wheel, on account of its great inertia and ease of operation in vacuum, will remain spinning and will give ample directive power for an hour or more after the power has been shut off, so that the compass is rendered fully effective under all such conditions. This constitutes a unique and extremely valuable feature of the Sperry compass.

An independent six-volt battery and alarm bell are employed to notify the attendant promptly of any interruption of current or failure in operation of various parts of the system which would be likely to cause errors in the compass readings, so that the same may be corrected without delay. A trip relay is provided which keeps the bell ringing until the attendant has corrected the difficulty and reset the trip.

A reverse current relay is provided for disconnecting the direct-current dynamotor from the storage battery and line upon failure, or any material reduction in voltage of the generator or ship's supply line, and for connecting the generator in again when voltage has been restored to normal. This of course prevents the rapid discharge of the storage battery in driving the generator.

Especially designed switches and controlling apparatus are provided, which include a small and compact switch for throwing both the voltmeter and ammeter at once upon any one of a number of different circuits or phases. These switches are of the rotary or controller type and are enclosed in gas-tight cases to prevent danger of explosions when used in submarines.

The gyro motor is of the three-phase induction type, the squirrel-cage secondary forming a rigid part of the inner rim of the revolving wheel shown in Fig. 11.

On account of the high speed of the rotation, wheels have to be given a very careful running balance, which is accomplished by the use of various size studs threaded into holes at the periphery of the wheel on each side.

The stator also shown in Fig. 11 is mounted on one side of the main vacuum casing containing the wheel. A spiral line is painted on the wheel which, when observed through a window in the casing by means of a stroboscope, enables one quickly to determine the speed of rotation.

The servo-motor or follow-up system forms an important part of the gyro compass and performs three functions, of which the first is to shield the gyro from all external forces and friction. This is accomplished by the method of carrying the supporting filament, and all guiding bearings having to do with the sensitive element, within an outer frame known as the phantom (Fig. 12), which completely shields the element from all disturbing external forces.

The suspended mass of the sensitive element, which, including the wheel casing and the vertical supporting ring, weighs about seventy-five pounds, is by the above means rendered actively sensitive to a force couple of 1/4500 in-lb., which represents a force of less than one four-millionth part of its own weight acting at a radius of one foot. This degree of sensitiveness is actually measurable in the operation of the compass, which is thought to be somewhat remarkable in this respect.

A second function of the servo-motor, which in the gyro compass is known as the "azimuth motor," is to operate the transmitter for sending out indications to any number of repeater compasses located at distant parts of the ship. The main azimuth scale of the compass is also carried on the power-driven member.

The third function of the azimuth motor is to operate the

correction device before mentioned, which by means of cams solves a trigonometric equation involving the factors of speed, latitude and heading of the ship, and automatically introduces the proper correction into the compass readings, which are therefore maintained accurately upon the meridian. Fig. 13 shows the front of the correction device and dials which are set at the proper speed and latitude.

The azimuth motor with its reduction gearing is shown in Fig. 14, and is provided with ball bearings throughout. An inertia brake consisting of a balance wheel mounted and driven by friction on the armature shaft serves to damp the oscillations or hunting of the azimuth motor, while offering no resistance to continuous motion.

The secondary transmission system comprises a contact-making transmitter and six-pole step-by-step motor connected by three circuits having a common return wire. The transmitter (Fig. 15) is provided with three pairs of tungsten make-and-break contacts which are operated by cams. The construction of the repeater system is such that the motor may be driven at speeds as high as 1000 rev. per min., or 100 cycles per second, without getting out of step.

The repeater motor is geared to give six steps for each indicated degree in azimuth and the repeater compass instantly follows all changes of the master compass for every movement of the ship. The repeaters are provided with compass cards made of translucent material to permit of illumination from within.

A manually operated transmitter, or synchronizer, is used for setting the distant repeaters into agreement with the master compass in connection with a magnetic stop for each motor by means of which the repeaters are first collected upon a common reading and then brought at once to read with the master, which is then thrown into circuit.

The exceptionally fine results obtained with the gyro compass here described have fully justified the long and painstaking efforts that have been expended in its design and in the practical solution of the many problems met at various stages of its development and in actual use at sea.

When subjected to the most drastic tests, far greater in severity than any actual conditions found on shipboard, the compass continues to hold to the meridian within a fraction of a degree. In fact, every compass before being accepted by our Government has to pass through a series of such tests lasting several weeks,

during which time the maximum error must not exceed ½ deg. in azimuth when swung continuously for six days at a time under conditions of rolling, pitching and yawing of an artificial ship.

It should of course be understood that under similar conditions on board a battleship or submarine the magnetic compass would be almost if not entirely useless. Even under the best of conditions, navigation of a steel ship by magnetic compass entails a large amount of extra work with considerable liability of error in applying variation and deviation corrections of various amounts, plus or minus. With the gyro compass described, all readings are made exactly upon the meridian and the navigator is always sailing on true courses. The quick and accurate indications of the compass for the slightest deviation or yawing of the ship have enabled much straighter courses to be steered, with a resulting saving in fuel and increased speed. For intricate maneuvering in battle practise, the ship may be controlled perfectly from various protected steering stations and the master compass is completely shielded from the fire of the enemy and from the shock of gun fire.

In submarines the gyro compass enables an accurate course to be laid when running submerged, so that after obtaining the bearing of the target from a great distance the submarine may approach, submerged, to within a short distance and fire its torpedoes accurately.

From an instrument having a degree of sensitiveness to force couples measured by one four-millionth part of its own weight it is rather a long jump to consider another type of gyro possessed of many tons of stored energy which may be harnessed and made to work not only to hold a mammoth ship against rolling in high seas but actually to roll the ship for the purpose of sliding off a sand bar or breaking through an ice floe.

Gyros of this type have already been built, tested and thoroughly investigated and a gyro of thirty tons weight capable of exerting a force couple of over four million pound-feet is now under construction for stabilizing the S. S. *Ashtabula*, used as a car ferry on Lake Erie.

In two papers read before the Institute of Naval Architects and Marine Engineers in November 1912 and December 1913, Mr. Sperry has treated very ably and comprehensively the subject of stabilizing ships and has made some striking comparisons which show his valuable contribution to the art in the

" active " type of gyro. In the last paper referred to are shown characteristic rolling and damping curves for ships equipped with active gyros, when subjected to various wave impulses and frequencies. These curves, some of which are here reproduced in Fig. 16, were obtained from a model ship pendulum, the dimensions of which were adjusted to correspond to a 19,000-ton ship at the linear ratio of 1:30.

The stabilization is practically complete, as indicated by the curves in Fig. 16. Early in this work, observations were made indicating that the stabilization was complete even when the wave increments received from the sea were greater than the theoretical power of the gyros mounted in the ship.

The work with the stabilizer has shown that it is perfectly easy to stabilize against all wave increments received by the ship from the sea which are equal to or less than the stabilizing capacity of the gyro equipment. Stabilization is so complete under these conditions that interest in this part of the performance has been transferred to investigations of the region where the wave increments are actually in excess of the stabilizing capacity.

The curves in Fig. 16 are among the results obtained in this connection and it will be seen by carefully scrutinizing the cards that none of the curves are taken where the wave increments are not larger than the roll-quenching increment, and even under these conditions the stabilizing is practically complete for practically all the wave periods.

Practical data of great value were obtained from the construction of an active gyro plant which was tested out repeatedly on the U. S. S. *Worden* during the summer of 1912. This plant was the largest gyro installation ever built and consisted of two gyros weighing about three tons each which were operated actively by use of a precession engine.

The gyros were automatically controlled so that they responded instantly to all wave increments encountered, whether in harmony with the period of the ship or not.

Fig. 17 shows one of the *Worden's* gyros bolted on a heavy base plate while under test at the Brooklyn Navy Yard. The base was loaded with pig iron, which, with the load of the gyro and precession engine, brought the total weight up to over thirty tons. The gyro very effectively demonstrated its power by actually lifting this heavy load, tilting the whole base plate up on edge and rocking it back and forth as the gyro was precessed.

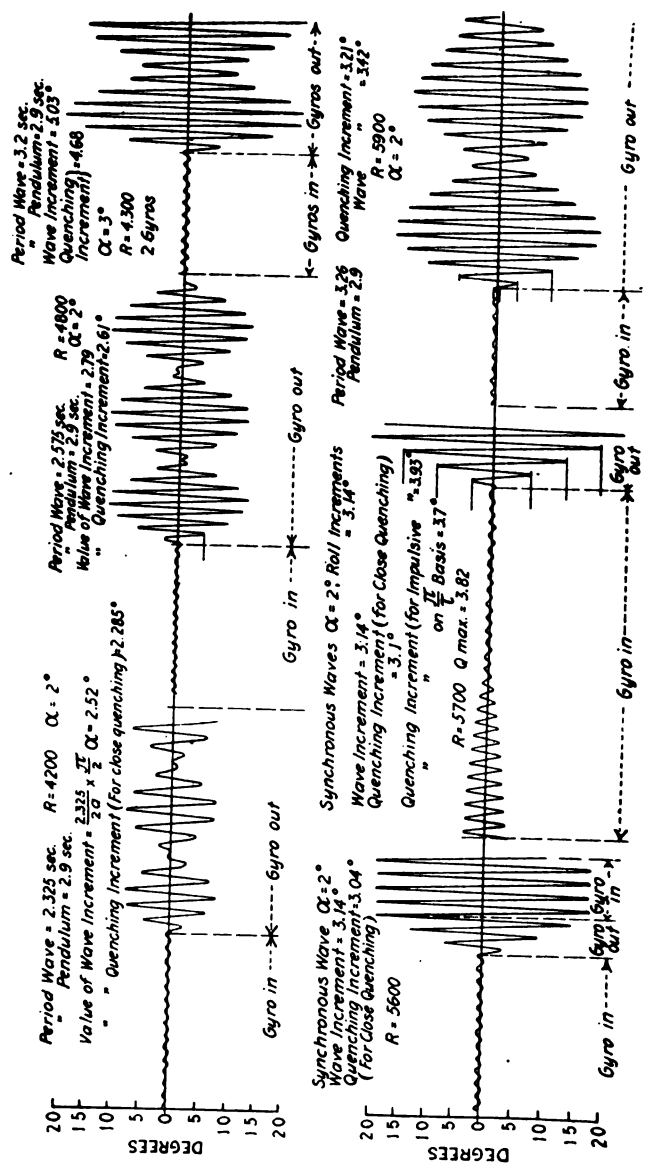

FIG. 16—CURVES SHOWING THE PERFORMANCE OF THE "ACTIVE" TYPE OF GYROSCOPE IN STABILIZING A PENDULUM SHIP MODEL AGAINST WAVE FORCES GREATER THAN THE THEORETICAL POWER OF THE GYRO

FIG. 19 [FORD]

The U.S.S. *Worden* at Dock.

Fig. 18 shows the precession engine, and Fig. 19 shows the gyro equipment mounted aboard the *Worden* ready for the sea trials.

The results prove conclusively that the active type of gyroscope as applied to the control of a ship's rolling motion is of vastly greater efficiency and economy than any other form of stabilizer yet proposed. The efficiency is demonstrated by the action of carefully calculated scale models and is completely verified by the long-continued performance at sea of the gyro plant on the *Worden*. The economy is evident from a comparison of the space and weight required in an installation of the active gyro relative to that required by the most effective form of water damping tanks or other stabilizing means.

Careful calculations show that an active gyro plant for stabilizing the S. S. *Ashtabula* will require less than one-tenth the space and weight which would be necessary for equivalent stabilizing with the best-designed water pendulum.

The results further show that it is now possible completely to stabilize any ship against rolling by means of an active gyroscope, requiring a very small percentage of the weight and space available in the ship. This work has opened up a wide field of usefulness in the application of the gyroscope.

DISCUSSION ON "THE ELECTRICALLY DRIVEN GYROSCOPE IN MARINE WORK" (FORD), DETROIT, MICH., JUNE 23, 1914.

Alfred E. Waller: There are two points I would like to ask Mr. Ford to explain further. One of them is, just what position the gyro occupies in the ship; for instance, just what is done to it to produce this rolling which has been shown to be so effective in breaking ice and getting a ship through a channel which would otherwise be obstructed?

The other thing I would like to have explained more in detail is this: I understand that the directive force of the gyro is a certain component of the angular motion of the earth, and at the poles this would be zero, so this should render the gyro ineffective at the poles. I would like to know to what extent the gyro is affected by extreme north or south latitudes.

H. C. Ford: The method of rolling the ship simply consists in forcing the precession or oscillation of the gyro about its vertical axis. When the ship rolls, the gyro tends to precess, and if this precession is allowed to occur, resisting forces will be set up proportional to the velocity of precession, which will partially stabilize the ship. To stabilize the ship completely it is necessary so to control the precession in time and amount that the varying wave forces are each counteracted by an equivalent gyroscopic moment. By forcing the precession, energy may thus be transferred through the gyro and the ship made to roll.

The gyro may be located in any convenient space that is available where the necessary bracing can be secured to the frame of the ship. Although the forces are large they are not excessive, being approximately of the same order of magnitude as the wave forces counteracted. It has been found that when stabilized, the ship is subjected to less strain than when allowed to roll freely. This is partly due to the fact that the waves are neither uniform nor synchronous with the roll of the ship. The freely rolling ship rides some waves easily, but frequently gets out of step and crashes into a wave with much greater shock than is the case with the stabilized ship, where the effect of the variable waves is reduced to a moderate average.

The size of gyroscope required to stabilize any ship depends entirely upon the proportions of the ship, which vary greatly in ships of a given tonnage. The gyro designed for the steamship *Ashtabula* is much larger than would be required for other ships of the same displacement, which would ordinarily have a smaller metacentric height. It may seem strange that the flatter, the more stable, a ship is, the more it will roll in a heavy sea, while a ship proportioned more like a cigar, with a low metacenter, will not roll, although it might capsize. The latter could be effectively stabilized with a very small gyro. The weight of the gyro installation required for any particular case cannot be given without quite extensive calculations.

Presented at the 31st Annual Convention of the American Institute of Electrical Engineers, Detroit, Mich., June 23, 1914, under the auspices of the Industrial Power Committee.

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DIRECT-CURRENT MOTORS FOR COAL AND ORE BRIDGES

BY R. H. MCLAIN

ABSTRACT OF PAPER

This paper gives a brief description of the mechanical arrangement of a coal bridge. The bridge consists essentially of a trolley car with hoisting mechanism for a self-filling bucket. A series-wound motor is recommended for driving the trolley car; and the proper method of gearing the motor for the most economical results is discussed. A series-wound motor is recommended for a low-speed hoist and a shunt-wound motor for a high-speed hoist. The relative merits of the two methods of winding the motor are considered.

A MAN trolley type coal or ore bridge consists essentially of a trolley car on an elevated railway carrying a self-filling bucket, with machinery for hoisting, lowering, opening and closing the bucket. The name of this type of bridge comes from the fact that the operator rides in the car. The bucket is suspended on two ropes, a " closing line " and a " holding line." If the holding line is stationary, the bucket will close when the closing line is taken in and will open when the closing line is let out. The elevated track or bridge spans a storage pile and usually extends out over a slip of water to cover a boat and often extends over railroad tracks on the other end. The bridge is supported on rails and can move along the storage pile.

Either one motor or two motors, in parallel, are used for propelling the trolley car. Generally two motors are used—one at one end and one at the other end of the car—so as to get uniform weight distribution and maximum tractive effort from the car wheels. Two hoist drums are used, one for the closing line and one for the holding line. The closing line drum is geared directly to a motor, while the holding line drum may be either driven from the closing drum through a clutch or geared to a separate motor.

Sometimes it is deemed advisable to use two motors geared together, instead of one, so as to get mechanical advantages in the trolley, such as even distribution of weight, and so on. For pur-

poses of this paper we will consider that one motor is used for propelling and that one motor does all of the hoisting. Where two motors are geared together and used as one, the characteristics are the same as if one motor were used, except that special precautions are taken in the design of the controllers to make the motors divide their loads properly.

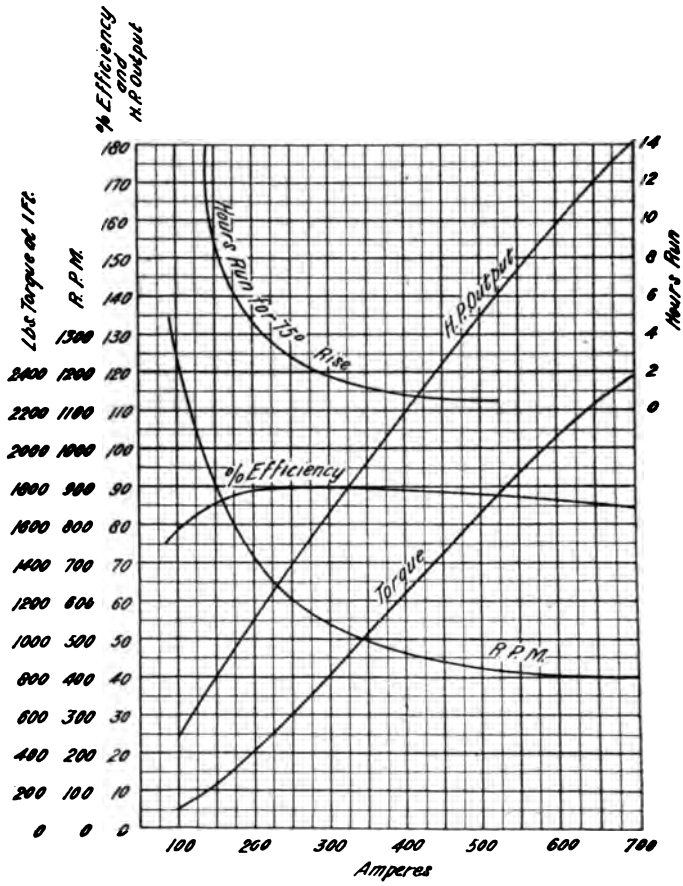


FIG. 1—SPEED-TORQUE-CURRENT CURVES OF A 100-H. P. SERIES-WOUND MOTOR

The problem for the propelling service is to move the car back and forth over the storage pile, making trips of various lengths, as quickly as possible. The distances vary from 50 to 600 ft. (15 to 180 m.), and the car speeds may reach a maximum of 1500 ft. (460 m.) per minute. A series-wound motor is well adapted for this service because it exerts about 50 per cent greater torque

per ampere on starting than on running. This feature makes a considerable saving in power consumption and power peak, as well as in the size of the motor, because most of the work of this motor is the starting and stopping of the trolley. The usual acceleration for the trolley is 1.5 to 2.5 ft. (46 to 76 cm.) per second per second. The speed for which the trolley is geared to run after all accelerating is completed—the "free running speed"—should be determined from the distance to be traveled and the time allowed for making the trip. For short trips the free running speed should be low and the accelerating rate high; while for long trips the free running speed should be higher and the accelerating rate lower. On a given coal bridge the average

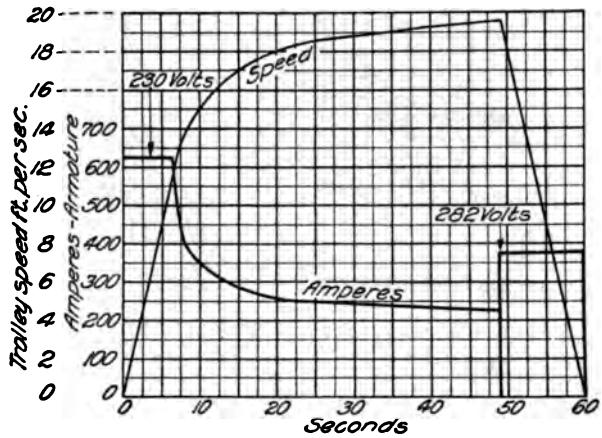


FIG. 2—SPEED-TIME AND CURRENT-TIME CURVES OF A 45-TON MAN TROLLEY, GEARED TO A 100-H. P. SERIES-WOUND MOTOR

Maximum speed of motor, 655 rev. per min.; maximum speed of trolley, 19.75 ft. per sec.

length of trip should determine the values to be used. In order to study the problem the writer has made up a number of curves showing the distance traveled in given times for various free running speeds and various rates of accelerating. These curves were made by plotting speed-time curves and integrating them to find the distance traveled.

Fig. 1 shows the speed-torque current curve of a series-wound motor. If this motor is geared to a trolley whose weight is 45 tons,* gear loss 10 per cent, rolling friction 35 lb. (16 kg.) per ton, free running speed 19.75 ft. (6.02 m.) per second, acceleration and retardation 1.8 ft. (55 cm.) per second per second, the speed-time curve will be as shown in Fig. 2. The area of this curve

*1 short ton = 0.90718 metric ton.

represents the distance traveled by the trolley in 60 sec. Figs. 3 and 4 show the net results of a number of curves like Fig. 2. Fig. 3 shows feet traveled plotted against seconds for free running speeds between 7.5 ft. (2.3 m.) per sec. and 25 ft. (7.6 m.) per sec., acceleration and retardation being taken as 1.5 ft. (46 cm.) per sec. per sec. Fig. 4 is like Fig. 3, except that 2 ft. (61 cm.) per sec. per sec. is used.

It is interesting to note on Fig. 3 that if only 75 ft. (23 m.) is to

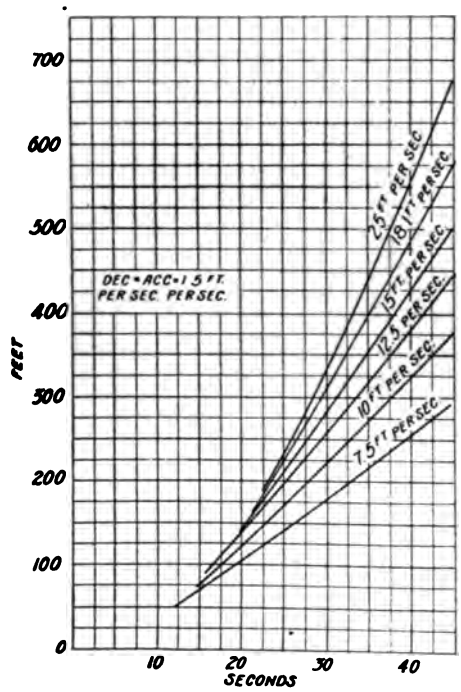


FIG. 3—DISTANCE-TIME CURVES FOR A 45-TON MAN TROLLEY GEARED TO A SERIES-WOUND MOTOR FOR "FREE RUNNING SPEEDS" VARYING FROM 7.5 TO 25 FT. PER SEC.

Acceleration equal to retardation equal to 1.5 ft. per sec. per sec.

be traveled it will take 14.5 sec. no matter whether the free running speed is more than 10 ft. (3.05 m.) per sec. or not. Consequently for 75-ft. (23-m.) trips there is no need of gearing for more than 10 ft. (3.05 m.) per sec. Likewise for a 150-ft. (46-m.) trip there is no need of gearing for more than 15 ft. (4.6 m.) per sec. It is easily understood that where low trolley speeds are used a given drawbar pull for accelerating can be obtained with the expenditure of less power than when high speeds are used.

It is also interesting to note that if 225 ft. (68.5 m.) must be traveled in 25 sec. and an acceleration of 1.5 ft. (46 cm.) per sec. per sec. (Fig. 3) is used, the free running speed must be 18 ft. (5.5 m.) per sec.; while if 2 ft. (61 cm.) per sec. per sec. (Fig. 4) is used, the free running speed need be only 13 ft. (3.9 m.) per sec. For distances less than 225 ft. (68.5 m.) the first method of gearing would require more time per trip and for distances greater than 225 ft. less time.

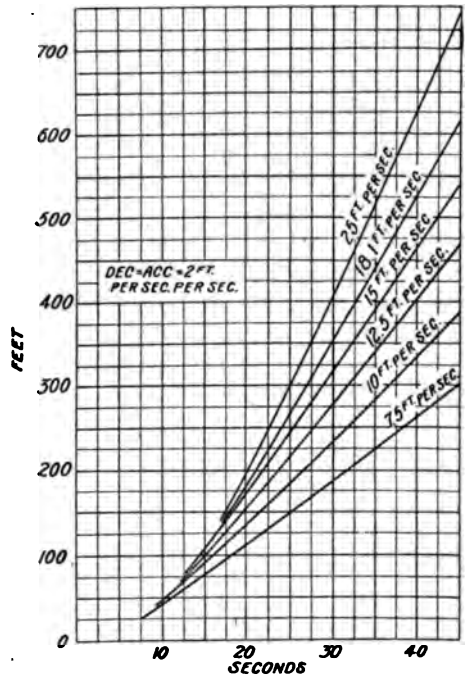


FIG. 4—DISTANCE-TIME CURVES FOR A 45-TON MAN TROLLEY GEARED TO A SERIES-WOUND MOTOR FOR "FREE RUNNING SPEEDS" VARYING FROM 7.5 TO 25 FT. PER SEC.

Acceleration equal to retardation equal to 2 ft. per sec. per sec.

For the control of a rack motor, simple rheostatic control of the automatic magnetic type should be used. On account of the large amount of kinetic energy to be dissipated when stopping the trolley it is advantageous to use the motor as a generator for stopping and thus save the maintenance of mechanical brakes. To obtain this braking, the armature, series field and a rheostat should be connected in such relation that the field will build up and the armature generate as shown in Fig. 5. The value of resis-

tance should be such that at the maximum speed of the motor sufficient current and voltage will be generated to give the desired rate of braking. As the generator speed decreases, the resistance should be decreased so as to maintain a uniform current and consequently uniform braking torque.

To determine the conditions of motor load let us take the case of the motor in Fig. 1 geared to the load described in Fig. 2.

Weight of load = 45 tons.

Rolling friction = 35 lb. (16 kg.) per ton when accelerating.

Gear loss = 10 per cent.

Motor so geared that 655 rev. per min. corresponds to 1185 ft. (361.2 m.) per min. or 19.75 ft. (6.02 m.) per sec.

Acceleration = retardation = 1.8 ft. (55 cm.) per sec. per sec.

Assume rolling friction 30 lb. (13.6 kg.) per ton when slowing down.

Assume gear loss 5 per cent when slowing down.

Pounds torque at one-ft. radius* required to accelerate the motor to 655 rev. per min. in 11 seconds = 74.5.

Then

$$\text{Drawbar pull to accelerate} = \frac{45 \times 2000 \times 1.8}{32.2} = 5040 \text{ lb.}$$

(2286 kg.).

Drawbar pull for rolling friction = 45 × 35 = 1570 lb. (712 kg.).

$$\text{Torque to accelerate load} = \frac{5040 \times 1185}{655 \times 2 \times \pi \times 0.90} = 1610$$

lb-ft.

$$\text{Torque to propel} = \frac{1570 \times 1185}{655 \times 2 \times \pi \times 0.90} = 500 \text{ lb-ft.}$$

Torque to accelerate armature = 74.5 lb-ft.

Total torque required while accelerating = 2184.5 lb-ft.

In Fig. 1, 2184.5 lb-ft. torque corresponds to 630 amperes. After all starting resistance is short-circuited and the motor is connected to 230-volt supply its speed will be (from Fig. 1) 405 rev. per min., which corresponds to 12.2 ft. (3.7 m.) per sec. Time required to attain this speed will be (12.2 ÷ 1.8 =) 6.8 sec. After this speed is attained the acceleration will be gradually reduced until uniform speed is attained. In Fig. 2 is plotted the current which corresponds to the speed and accelera-

*1 lb-ft. = 0.1383 kg-m.

ting rate of the car. After 19.75 ft. (6.02 m.) per sec. is attained, (19.75 ÷ 1.8 =) 11 sec. will be required to stop.

Drawbar pull to retard =

$$\frac{45 \times 2000 \times 1.8}{32.2} = 5040 \text{ lb. } (2286 \text{ kg.}).$$

Drawbar pull for rolling friction = 45×30 = 1350 lb. (612 kg.)
Net required drawbar pull = 3690 lb. (1674 kg.)

Net torque corresponding =

$$\frac{3690 \times 1185 \times 0.95}{655 \times 2 \times \pi} = 1010 \text{ lb-ft.}$$

Torque to retard motor = 74.5 lb-ft.
Total torque to retard = 1084.5 lb-ft.

From Fig. 1, 1084.5 lb-ft. torque corresponds to 375 amperes and 500 rev. per min. If we assume that the motor has an internal resistance of 0.04 ohm its internal voltage with an excitation of 375 amperes at 500 rev. per min. will be 230 − (375 × 0.04) = 215 volts. At 655 rev. per min and 375 amperes the internal voltage will be approximately $\frac{655}{500} \times 215 = 282$ volts.

The resistance in series with the armature must therefore be 282 ÷ 375 − 0.04 = 0.715 ohm.

A series motor will build up as a generator when its field and armature are connected in the proper relation, but it takes several seconds for this to take place. Therefore it is advisable to excite the field separately with a small amount of current so as to hasten this action. Now, even with separate excitation, about one second more may elapse before full magnetic strength is attained. During this time there has been some braking action from the motor, so that by the time full magnetism is attained, the speed is less than 655 rev. per min. and the voltage never attains the value of 282 which was calculated.

When the time constants of the magnetic field and the absolute voltage and current capacity of a motor are well known it is possible to get results in braking which are far superior to the calculated conditions in Fig. 2. The retardation may be made much greater without overloading the motor in either current or voltage or kilowatt output. Fig. 5 shows the connections for a rack motor controller which gives power and dynamic braking in both directions of rotation. The resistance blocks

must be proportioned not only for smooth accelerating but for retarding in the proper manner to suit the motor characteristics.

For hoist service we have the choice of series, compound or shunt-wound motors. The conditions which affect the choice are voltage variation, amount of power available, height of hoist and time required for the trip. A voltage variation of 10 to 20 per cent is usual. The power supply is generally limited, or at any rate peaks are penalized. The height of hoist in some locations is as low as 40 ft. (12 m.) and in others as high as 180 ft. (55 m.). Time allowed for the hoist may be anywhere from 6 to 15 sec.

The hoisting speed is of course fixed by the distance and time. Where a low speed is used, the time of starting and stopping is unimportant, but for high speeds the time consumed in this way

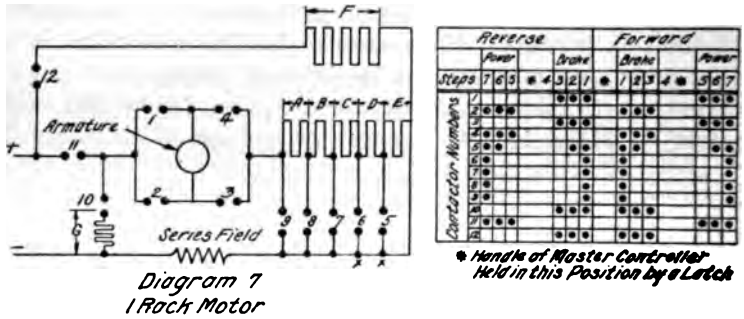


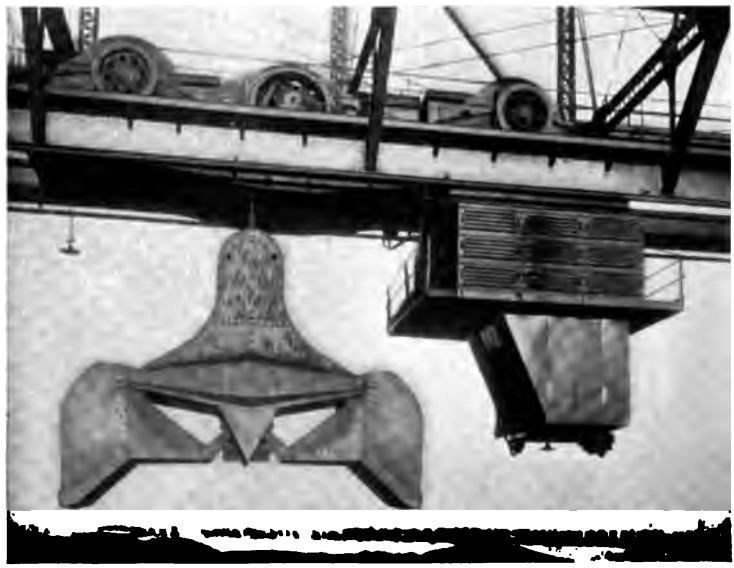
FIG. 5—CONTROLLER CONNECTIONS OF A SERIES-WOUND PROPELLING MOTOR ON A MAN TROLLEY COAL BRIDGE

is all-important. It is my opinion that a series-wound motor should be used for speeds of 360 ft. (110 m.) per min. or less if the height of hoist is such that at the speed used more than 8 sec. are consumed in the trip. For greater speeds and shorter time periods a compound-wound motor should be used. For still greater speeds of, say, 700 ft. (213 m.) per min. or more, a shunt-wound motor should be used. In order to present my ideas I will use two extreme examples.

Let us take a speed of 300 ft. (91.5 m.) per min., or 5 ft. (1.52 m.) per sec., a height of 40 ft. (12 m.) and a bucket which has 35 ft. (10.6 m.) of rope to be taken up while it is closing. It is possible on such a bucket to let the motor run at full speed while the bucket blades are in the act of coming together and the bucket is starting up; therefore no time is lost by running at re-

[MC LAIN]

FIG. 7—VIEW OF A MAN TROLLEY COAL BRIDGE SPANNING A COAL STORAGE PILE AND A BOAT



[MC LAIN]

FIG. 8—VIEW OF BUCKET AND TROLLEY USED ON BRIDGE IN FIG 7.

duced speed from the time the motor attains full speed in starting to close until the bucket is fully hoisted. If a shunt motor were used, 1.5 sec. would be required to start, 1 sec. to stop and 13.75 sec. would be required for full-speed running to wind up the whole seventy five ft. (22.8 m.) of rope. This makes a total of 16.25 sec. to make the trip. If a series motor were used, the same time would be required, except for the fact that while the bucket is being closed the load on the motor is small and the motor speeds up. The motor will run about 30 per cent above normal speed for most of the closing period, but toward the end of this period the load increases and the speed comes down to normal. About one second is saved by the series motor on each trip. Therefore the shunt motor would have to be geared for 6 per cent more speed in order to make the trip as quickly as the series motor, and would take 6 per cent more power while hoisting at full speed. Automatic current limit control is used on these motors; and since, at times, it is necessary to start the bucket from midair, the relays must be set for a current which will be great enough to start the loaded bucket even at the lowest line voltage. No more than this current is required, because the time of starting is unimportant. When a relay drops and a contactor short-circuits a block of resistance, there is a consequent current peak. For a given number of contactors, the ratio of these current peaks to the current at which a relay drops is at least 10 per cent more for a shunt than for a series motor. Furthermore, the current at which a relay drops must be made greater on a shunt motor, because, on low voltage and consequently weakened field, more current is required for a given torque than is required on a series motor whose field strength is not affected by voltage variation. On 80 per cent of normal voltage the current in a shunt motor may increase as much as 10 or 20 per cent. Summing up the above statements, we see that the starting current on the shunt motor will be about $(1.06 \times 1.10 \times 1.15 =)$ 1.34 times the starting current on a series motor. The series motor has the further advantage that when the bucket is not digging much coal and the weight is reduced, the speed will increase. Another advantage is that the series motor can stand the rapid voltage fluctuations with no damage, while a shunt motor may be damaged.

On high hoist speeds all of the advantages mentioned above for the series motor disappear, and a very decided advantage appears for the shunt motor. At these high speeds it is import-

ant that the full hoisting speed be as nearly constant as possible, regardless of voltage or load. The speed of a series motor may vary at least 30 per cent more, under service conditions, than that of a shunt motor. If the speed is say, 15 ft. (4.57 m.) per sec., 30 per cent variation means 4.5 ft. (1.37 m.) per sec. An operator cannot be expected to hoist to the correct height under such conditions without wasting considerable time running at low speed just before stopping at the top. Another advantage of the shunt motor is that it is very easy and simple to provide dynamic braking for stopping at the top so that no time need be wasted in getting stopped.

Let us take the example of 900 ft. (274 m.) per min. or 15 ft. (4.57 m.) per sec. speed, and 90 ft. (27.4 m.) height. A shunt motor will close the bucket as quickly as a series motor because the bucket will not dig properly if either motor runs at full speed. It is necessary to slow down or stop just as the bucket blades close, because the speed is so high. In order to make it worth while to use such a high speed, not over 3 sec. can be allowed for accelerating. This means that a rate of 5 ft. (1.52 m.) per sec. per sec. is used for acceleration or an extra pull of 15.5 per cent on the bucket. About 15.5 per cent additional pull is required to accelerate the drums and gears. In most cases a torque equivalent to 50 per cent of the pull on the bucket is required to accelerate the motor armature. The total torque required for accelerating in 3 sec. and for hoisting is therefore 181 per cent of the torque required for hoisting alone. In order to accelerate so quickly the current relays must be set to drop down at 145 per cent of the hoisting current. This is so high above normal that even on 80 per cent voltage the motor will start and therefore no extra current peaks are encountered, as would be the case on a low-speed hoist. There would, however, be greater peaks of current caused by the short-circuiting of the starting resistance, unless the field were made especially strong for starting and then reduced to normal strength during full speed running. An increase of speed due to a light load is a disadvantage on such a high speed because it deceives the operator and causes mistakes in the height to which the bucket is hoisted. A motor which has enough reserve capacity on its commutator to stand the 81 per cent overload encountered at starting will not be liable to much damage from fluctuating voltage, and therefore no extra cost need be put into the motor to make it stand this condition.

As mentioned above, it is advantageous to stop at the top with

dynamic braking on a high-speed hoist. If the motor is geared directly to its load the combined motor and load, for the case of 900 ft. (274 m.) per min. speed above stated, would coast (0.81 × 3 =) 2.43 sec. after power is shut off, and in this time would travel (2.43 × 15 ÷ 2 =) 13.2 ft. (4 m.) One second of this time could be saved by waiting till the bucket is within 7.5 ft. (2.3 m.) of the top and then applying full capacity of the motor as a brake by connecting resistance in parallel with the armature. Such an arrangement has other practical advantages. For example, if the bucket is just starting out of a boat and is about to strike a hatch coaming, it is imperative that an easy means of making a quick stop be at hand.

It is common practise on low-speed hoists which use series motors to lower the empty bucket by dynamic braking. All

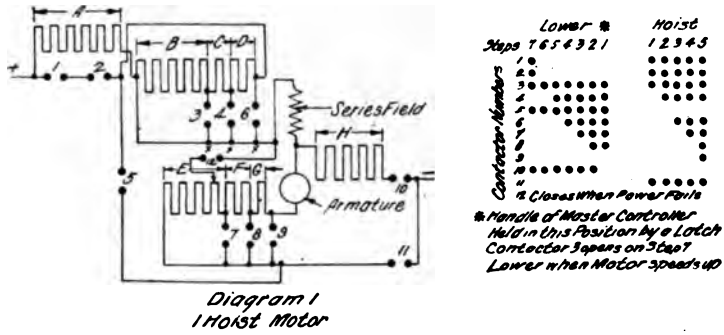


FIG. 6—CONTROLLER CONNECTIONS OF A SERIES-WOUND HOIST MOTOR ON A COAL BRIDGE

that is needed is to determine the torque on the motor shaft by making mechanical calculations. Find the current which flows in the motor, when this torque is exerted, by referring to the motor curve. Provide a rheostat in series with the armature and series field of such value that voltage drop in the rheostat with necessary current flowing will be equal to rated voltage of the motor. Many motors can stand more than rated voltage under this condition, because the current is relatively small. Thus the lowering speed can be much more than the hoisting speed. However, when this resistance is short-circuited to stop the motor, there is a large current peak which causes an increase in the motor voltage before the speed is actually reduced, because the current peak over-excites the field. It is, therefore, necessary to do this short-circuiting in several small steps, else

or multiple. We use dynamic braking on the lowering, but with only one of the motors on dynamic braking, *i.e.*, having only one motor perform the dynamic function. We had to do some scheming to get the arrangement of contactors which would allow us to hoist in multiple, and also use dynamic braking with one motor, but it can be done, and done very nicely.

R. H. McLain: In all large hoists of 5-ton bucket capacity and greater, I think I am perfectly safe in saying that dynamic braking is used, for the reason that friction brakes large enough to stand the wear and tear would take up too much room and be too expensive to maintain. That seems to be the present attitude of those designing these bridges. For smaller hoists this is not so generally the case. It is sometimes a matter of opinion, but I believe the most popular way is to use dynamic braking. Sometimes dynamic braking is used on the hoist motion alone and not on the racking motion, and at other times on both motions. The present status of the art was arrived at by a lot of trials with various ways of handling brakes. Of course, on hoist motion they always have mechanical brakes to sustain the load, but not necessarily to lower it.

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METHODS OF KEEPING DOWN PEAKS ON POWER PURCHASED ON A PEAK BASIS

BY T. E. TYNES

ABSTRACT OF PAPER

The author mentions two general ways of reducing peaks, the first being to furnish the peak power from a separate source such as a local steam turbine, and the second to store some of the power furnished by the power company, which is given up later when the peak demand comes on. In the case of the plant described by the author a mixed pressure turbine was installed to take the peaks, this being selected on account of available exhaust steam from pumps, air compressors, etc. The turbine is direct-connected to two direct-current generators mounted on a common bed-plate. The first plan tried was to use a motor-driven rheostat operated with clutches which in turn were operated by solenoids energized by current controlled by a contact-making ammeter.

After the installation of a maximum demand meter which integrates the one-minute peaks, the rheostat control was found to be too slow and a special peak-taking device was then installed. This device consists of a rod carrying points which successively make contact with mercury cups and which is operated by the moving element of the graphic meter. These mercury contacts close relay circuits which operate to short-circuit sections of resistance in the field rheostat of the turbo-generator, raising its voltage, and also cut in sections of resistance in the field rheostat of the motor-generator set, weakening its field and thus reducing its load.

THE BENEFICIAL results to be obtained by maintaining a good load factor are so well known, both to the producer and purchaser of power, as scarcely to need mentioning. From the producer's standpoint, the increased generating capacity made available, the better regulation obtained on the generating apparatus, and lower maintenance costs on generating apparatus due to absence of shocks from violent fluctuations of load, give results that are well worth striving for.

From the consumer's standpoint, especially those who pay on a peak basis, a high load factor is very desirable in that they receive more power for a given sum of money; or, in other words, their rate per horse power-hour or horse power-year is decreased.

There are several ways in which these desirable results can

be obtained by consumers of purchased power. They may be grouped under two general methods:

In the first method, the power demand represented by the peak is furnished from a separate source, such as a local steam turbine, hydroelectric or gas-engine-driven plant.

In the second method, the power required of the peak was previously furnished by the power company and stored by the purchaser to be given up later when the peak demand comes on. This storing of energy may be accomplished either by means of storage batteries, or, in case of frequent peaks of short duration, by means of heavy, rapidly revolving flywheels.

It is to be noted that in the second method the average demand on the power company is higher for a given total energy consumption by the purchaser than in the first method.

In the Institute TRANSACTIONS for 1911 a method of lopping off peaks on power furnished to ore bridges is described* by Messrs. Motter and Tatum. The results are accomplished by means of a d-c. machine on the shaft of which is mounted a flywheel. This flywheel set floats across the line and is either absorbing or giving up energy, according to the demands of the circuit to which it is connected, and may be called an electromechanical storage battery. By a suitable arrangement of relays and switches the set absorbs energy when the demand on the circuit is below a predetermined amount and gives up its stored energy when the demand on the circuit exceeds this amount.

In the following pages the writer will briefly describe a method by which an improved load factor was obtained on purchased power.

Some exhaust steam being available from hydraulic pumps and air compressors in the power house of the company with which the writer is connected, it was decided, after studying the conditions carefully, to install a mixed pressure turbine to take peaks, so as to get a more uniform load factor on the purchased power. The latter is delivered at 60,000 volts and stepped down to 2300 volts. At this voltage the greater part of it is used to drive synchronous motor-generator sets, and the remainder is further stepped down to 440 volts and used to drive three-phase induction motors.

As the greatest fluctuations and largest demand came on the

Flywheel Load Equalizer, TRANSACTIONS A. I. E. E., XXX, 1911, page 729.

FIG. 1 [TYNES]

FIG. 2 [TYNES]

FIG. 3 [TYNES]

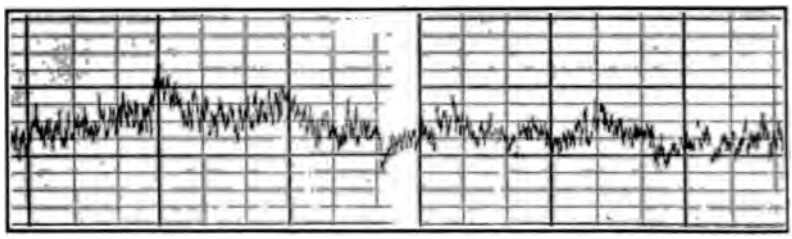


FIG. 7 [TYNES]

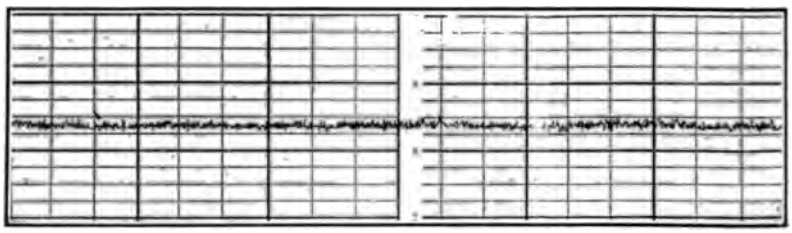


FIG. 8 [TYNES]

d-c. side of the motor-generator sets, it was found to be more efficient to generate direct current directly rather than generate alternating current and convert it to direct current through the motor-generator sets, a saving of at least 16 per cent being effected.

Accordingly a 750-kw. mixed pressure d-c. turbine unit was purchased, views of which are shown in Figs. 1, 2 and 3. The turbine is direct-connected to two 375-kw. 250-volt commutating-pole four-pole generators driven at 1500 rev. per min., all mounted on a common bedplate. The generators are mechanically coupled in tandem and electrically coupled in parallel. Each machine is complete in itself, so that if one machine fails the other can deliver its full output, making 50 per cent load on the turbine.

Power is purchased on the basis of the one-minute peak. At the time the turbine installation was planned, the one-minute peak was measured by a scale, the height of the peak being the point at which the one-minute space would just come within the boundary of the peak, shown by *A*, Fig. 4.

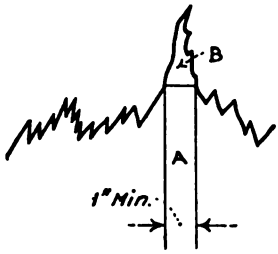


FIG. 4

The turbine would naturally respond to a change of load more quickly than the other apparatus, but would not, unassisted, take all the peak that it was desired that it should; therefore a motor-driven rheostat was furnished (Fig. 5), with two faces, one for each generator on the turbine. The small motor runs continuously, transmitting its power to a shaft at right angles to it. On this shaft are two clutches, one half of each of which is fastened on the continuously running shaft. The other half of each clutch is connected through gearing to the rheostat arms in such a manner that when one of the clutches is engaged the arms on the rheostats revolve clockwise and when the other clutch is engaged the arms rotate counter-clockwise. The clutches are interlocked so that only one can be in at a time. The clutches are operated by solenoids energized by current controlled by a contact-making ammeter.

About this time the power company perfected a maximum demand meter which integrates the one-minute peaks. They installed this instrument in our substation, with the result that our peaks jumped up from 8 to 12 per cent above those

previously obtained on the same load, due to the portion *B*, Fig. 1, being added by the integration, which by the scale method of measurement was not taken into account. Our load factor was of course lowered proportionately. This put us on our mettle to try, if possible, to regain our lost load factor.

We found the rheostat method of control too slow, as every second counted on that integrated peak, so we tried another

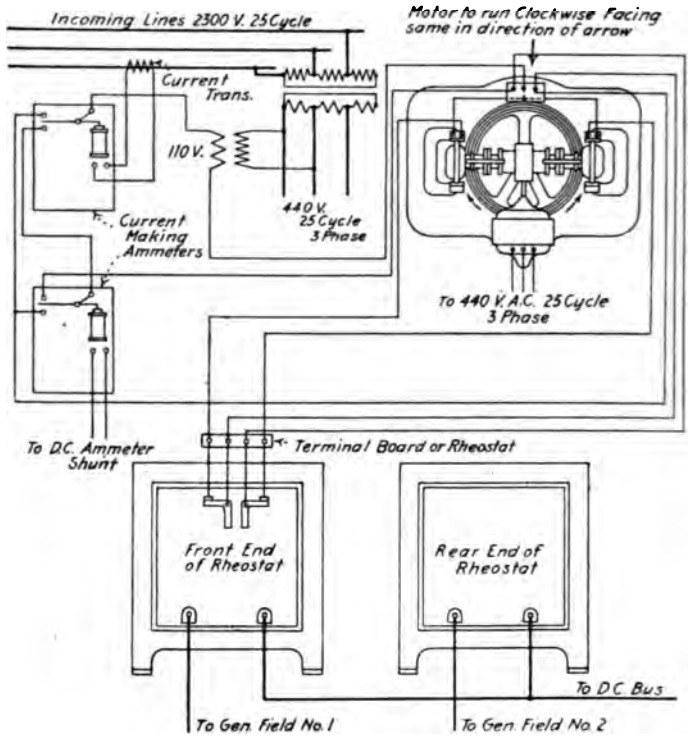


FIG. 5—CONNECTIONS OF TWO RHEOSTATS OPERATED BY SINGLE SHAFT WITH CONTACT-MAKING AMMETERS

scheme of control which is illustrated in Fig. 6, a description of which follows:

The piece *A* consists of a metal rod with three points, p_1, p_2 and p_3, projecting downward over the centers of three cups partly filled with mercury. p_1 is shorter than p_2 and p_3, which are the same length.

A is raised and lowered by the moving element of a graphic

recording wattmeter, which serves the double purpose of operating the peak-taking device and making a visible record of the load.

The points p_1, p_2 and p_3 are so adjusted that when the load reaches the predetermined amount at which it is desired it shall be held, the points p_2 and p_3 just touch the mercury, closing the circuit through the operating coil of contactor $C\,T_1$, which closes, short-circuiting a section of resistance in the shunt field rheostat of the turbine, raising its voltage and causing it to take more load. When $C\,T_1$ closes, it opens a relay in the circuit of the operating coil for contactor $C\,M_1$, which causes the latter to open, cutting in a section of resistance into the shunt field rheostat of the motor-generator set, weakening its field and reducing its load.

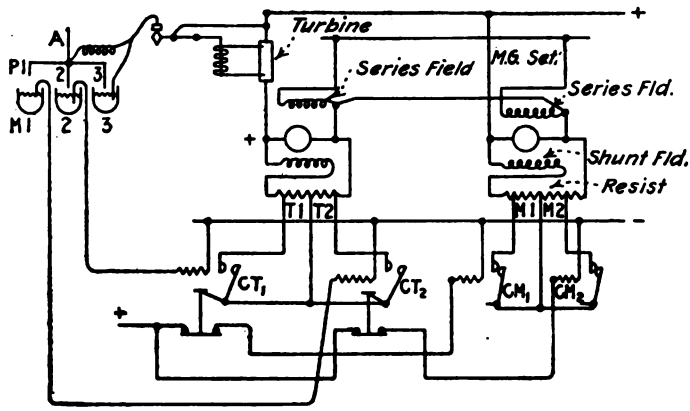


FIG. 6—DIAGRAMMATIC SKETCH OF PEAK-TAKING DEVICE

If the reduction of the load on the motor-generator sets and the increased load on the turbine is not sufficient to keep the peak down to the predetermined amount, the points p_1, p_2 and p_3 will be still further lowered, allowing p_1 to come into circuit, closing contactor $C\,T_2$, cutting more resistance out of the shunt field circuit of the turbine and cutting more resistance into the shunt field circuit of the motor-generator sets, causing a further increase of load on the turbine, and decrease of load on the motor-generator sets.

In order to protect the turbine from excessive overloads, a shunt is inserted in the positive leads of the turbine generators. The current around this shunt operates a contact-making ammeter, which opens and closes the circuit to the mercury

cups. It is adjusted to open the circuits at 50 per cent overload on the turbine. When the turbine reaches this load, any further increase in its load causes the contacts to part, opening the control circuit to contactors $C\,T_1$ and $C\,T_2$, which opens, and in opening closes the contactors $C\,M_1$ and $C\,M_2$. The result of these operations is to decrease the load on the turbine and increase it on the motor-generator sets until the turbine load falls below its overload limit. When this is reached the contactors $C\,T_1$ and $C\,T_2$ again close and $C\,M_1$ and $C\,M_2$ open, this action of the contact-making ammeter being similar to a voltage regulator.

When the load reaches the point below which we do not want to take peaks, the point p_1 is raised, breaking the circuit through contactor $C\,T_2$ and $C\,M_2$, causing the former to open and the latter to close, reducing the load on the turbine and increasing it on the motor-generator sets. A further decrease of load causes p_2 and p_3 to rise, opening the circuit $C\,T_1$ and closing the circuit $C\,M_1$, which causes the turbine to float on the line at a very light load and the motor-generator set to take full load or whatever demand may be made on it at the time.

The turbine installation has given excellent service and good commutation has been obtained in spite of the high speed of rotation (1500 rev. per min.).

An average curve, without the peak-taking device on, is shown in Fig. 7, while in Fig. 8 are shown practically the same conditions with the peak-taking device working.

DISCUSSION ON "METHODS OF KEEPING DOWN PEAKS ON POWER PURCHASED ON A PEAK BASIS" (TYNES), DETROIT, MICH., JUNE 23, 1914.

Rudolph Tschentscher: Power contracts, as you all know, are usually made on a peak basis, and the question of the reduction of these peaks is a most important one. I believe it is desirable to emphasize the point Mr. Tynes has mentioned, namely, that the reduction of peaks is of material benefit to the power generating company.

Paul M. Lincoln: This point that Mr. Tynes has raised is an exceedingly important one. Wherever power is taken from a hydraulic plant, the maximum demand method of charging is a logical one; no question about it. This is particularly true in the case of the hydroelectric plant where the water is not limited, such as the Niagara Falls plant. It does not matter to the power company whether the power is taken for 15 minutes, or one minute a day, or for the 24 hours continuously, it is the maximum demand which dictates the amount of the power bill, because the ability of the power company to supply power is limited by the output of the prime mover or of the generator. The fact that the power is taken continuously 24 hours a day merely means that the water is running through the wheels for that length of time, instead of running over the spillway. It is therefore perfectly logical for the power company to insist upon a system of selling on the maximum demand basis.

In the case of the steel company which Mr. Tynes represents, its power curve is anything but an even line of continuous demand. It also has its own apparatus for generating power, and his problem has been to so regulate his apparatus as to make the power taken from the power company show an even line, to so regulate his own apparatus that all of the excess above that even line is taken from his own steam plant. The method which he has used to secure that result is exceedingly interesting, and one of very great value.

J. Lester Woodbridge: This paper presents a special solution of a problem which undoubtedly exists very commonly in districts where power is purchased on the maximum demand basis. It would, perhaps, be interesting to compare the results obtained by this solution with those which might have been obtained by the application of a storage battery, but the data given in the paper are hardly sufficient to permit of such a comparison being made. Doubtless the solution adopted in this particular case was the wise one in view of the presence of exhaust steam which, I presume, was obtained without additional cost. The paper, however, does not give us the length or the height of the peak very definitely.

It would be interesting to have the financial results set forth in this paper as well as the technical results; for example, whether the operation of this turbine actually costs anything for fuel, that is, whether the steam was supplied without additional cost for fuel,

whether the exhaust steam was sufficient to operate the turbine, or whether some live steam had to be used; also whether the cost of attendance was increased. In fact, the total cost of operating the plant would be an interesting item, so that we might compare that with the saving effected. Possibly these figures might be added by the author in a subsequent discussion.

It would also be interesting to know the total power produced by the mixed turbine and the cost per kilowatt-hour to produce it. It also occurs to me to ask whether, if the power is obtained without cost by utilizing exhaust steam, the investment for the installation having once been made, it would be economical to operate this outfit to handle more than merely the peak load. Could it be operated 24 hours a day to take some of the body of the load itself, if it does not cost anything to operate? A number of these questions could perhaps be very interestingly discussed in an addition to the paper.

J. R. Bibbins: Considering this paper from the standpoint of the central station, I notice from Fig. 4 that a one-minute maximum is the basis upon which this system depends. It seems to me that the economic value of this whole peak-reducing apparatus depends greatly upon what duration of the peak is incorporated in the power contract. I have in mind a railway load in which the maximum demand is over 100,000 kw. The power contract involves a fixed rate primary or readiness-to-serve charge, proportioned to the maximum demand of an hour's duration (averaged over three successive days), and a secondary or service charge, dependent upon the output of the station, and with a sliding scale of rates per kilowatt-hour. This works out as follows: During the summer the maximum peak loads are very largely reduced, but the railway company continues paying for the maximum one-hour demand of the previous winter, and logically so, throughout the entire year. If a mild winter happens to occur, in which the heating and the additional friction load is reduced, these two factors combine to reduce the maximum peak and primary charge.

Now, the point that interests me here is the use of this one-minute maximum, and if we analyze a railway load it is very clear that the actual peak upon which such a primary charge depends is not always of as long duration as stated in this contract, *i.e.*, one hour. And so it occurs to me that there is a possibility of applying a shorter maximum period in power contracts for such large systems with primary charge adjusted in accordance with the relative overload capacity of the station. Referring back to the prime mover, it is very clear that, with the very large units now used and the great overload capacity available within reasonable limits of temperature rise, if we had a shorter maximum period than one hour the primary charge upon which it is computed might be considerably less than it is to-day.

In this particular case the contract worked out in a very

peculiar way. As the system expanded and the power load built up, it was found that the primary charge kept ahead of the secondary charge, with the net result that the total cost per kilowatt-hour actually increased as the power consumption of the railway increased. It seems rather illogical that with a load increasing from 60,000 to 100,000 kw. the net cost of power per kilowatt-hour, including these two factors, primary and secondary, should have risen under conditions of such an extremely large output. One explanation will occur, from the fact that any considerable improvement in the service of street railways necessarily means more service at rush hours. In fact, the street railway problem is almost entirely one of rush hours, and the additional equipment operated at the rush hours must necessarily increase the maximum demand for that period. So that as we demand from our street railway companies improved service, we must suffer a decrease in load factor and a higher primary charge.

I take it that from the prime mover end, there is little hope for the development of a special type of apparatus, other than the turbo-generator outfits that we already have, which would automatically absorb these high peaks, with the single exception of the combined hydraulic and steam power system which Mr. Lincoln mentioned.

So the specific question I raise, from the central station standpoint, is, whether this shorter period mentioned in this paper would not be equally as applicable to central station conditions as to the industrial load that is here described, *i.e.*, whether a one-hour maximum is entirely justifiable in cases where the real maximum for which the central station must provide apparatus is considerably less than one hour; in other words, whether we cannot take advantage of that fact and reach a more logical primary charge, so that the occurrence of a very short peak load occasionally, of considerably higher maximum than the hour would average, (but well within the momentary capacity of the equipment), will not become such a burden as it does in this case. Obviously, the shorter the duration of peak, the greater the margin of safe overload available from a given investment, and usually, in railway loads, the exaggerated peaks are of very short duration.

R. H. McLain: I would like to say a word about this matter of charging for peaks, based on one example that I am familiar with. There is a large number of coal docks and a street car load, all of which make up a very large part of the central station power load, and there was, before many coal docks began to buy power, a great deal of argument about how to charge for this power. In the beginning, the coal docks were charged on an instantaneous peak basis—that was the primary charge for them. As the coal docks increased in number, the load curve for the central station company became flatter and flatter. I do not know how they charge for the power now, but I know

enough about the system to know that it would be practicable for them to charge for five-minute peaks, or some other peak like that, and not take any account whatsoever of these one-second and one-minute peaks. I think that the central station companies should take a very broad-minded view of this situation, and when they serve a lot of power consumers should try to keep from putting the customer to a great deal of expense in cutting down his peak, when another customer across the road, or two or three more, might combine with this first customer in such a way as to make the entire load almost uniform. I firmly believe that the more the central station companies take this view into account in making their charges, the more popular will be the use of central station power; but, of course, for any one location the particular nature of the load should be taken into account.

E. D. Dreyfus: The ingenious method employed by Mr. Tynes to maintain a practically uniform load upon the power company's system has impressed me very much. No doubt Mr. Tynes has been able to effect a certain degree of economy in the operation of his plant which is probably due to fortuitous conditions such as the availability of an exhaust steam supply and the presence of operatives who can well afford to take care of the extra equipment necessary in addition to looking after their other duties. The situation is manifestly exceptional and therefore we should be careful that the idea does not become prevalent that the scheme described is possible of broad application.

According to my conception of the problem and from many investigations made in this direction, the trend of results tends to show that it is the low load factor business upon which the central station can most readily compete with the isolated plant. This is largely true for the reason that the so-called "stand-by" cost of the isolated plant (including capital charges, labor, banking and discrepancies) plays an important part in the total cost under low load factor conditions.

When operating at high load factors, these "stand-by" charges are spread over a large number of kilowatt-hours and therefore the unit cost is very rapidly reduced. I believe this can best be shown diagrammatically, and the accompanying illustration (Fig. 1), in which values are taken from a case selected at randon, will aid in establishing the truth of the proposition.

Obviously the comparative showing will in each case depend upon the assumptions made. There is a wide range in the operating results of different isolated power plants, naturally depending upon their equipment and the ability and faithfulness of the operating force. Two limits (one shown by heavy solid lines and the other by heavy dotted lines) for the isolated power plant operation are given so that this phase may be duly regarded. On the other hand, the cost of central station power for fixed

conditions is fairly uniform in the different geographical divisions of the country, and consequently a single line of costs has been included for central station power (shown by the heavy dot and dash line).

Hence, due to what may be termed the inherent slope of the total cost lines or curves, the relative rise with load is actually

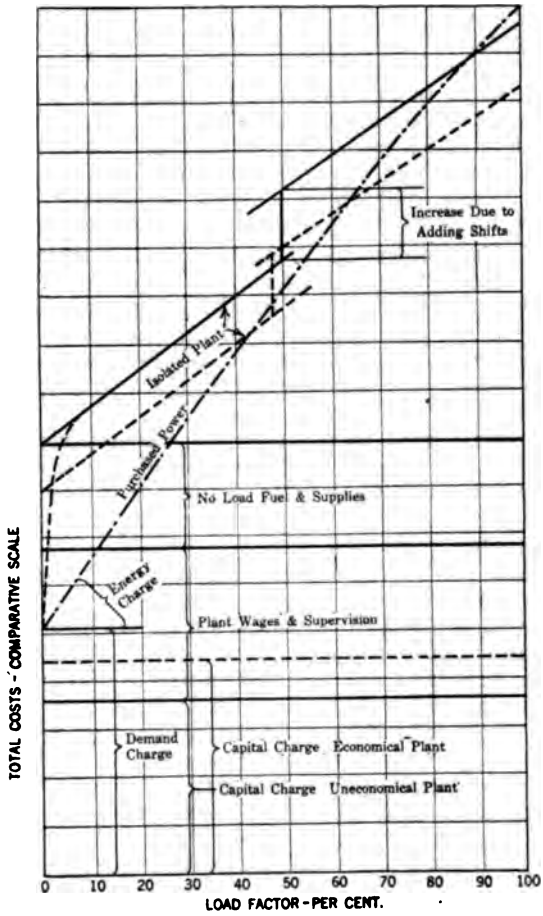


FIG. 1

in favor of the isolated power plant, and, as here indicated, the larger independent plant may show lower costs at points beyond 50 to 75 per cent load factor, provided all other handicaps have been overcome. While this argument is of a general nature it is sufficiently specific, I believe, to prove that unless the peak can be reduced by flywheel effect or by virtue of

The roughing stands are twelve in number, all two-high, and are driven through spur and bevel gears by a 44 by 60-in. (112 by 152-cm.) simple non-condensing Corliss engine, running at about 65 rev. per min. average speed. The number of roughing stands used depends upon the size of the finished bars. In rolling some of the larger sizes, but six or eight of the twelve stands are used.

From the roughing stands, the bars are delivered through pipe conveyers to the finishing rolls. These are four stands of two-high 11-in. (28-cm.) diameter rolls, and were formerly belt-driven by a 28 by 36-in. (71 by 91-cm.) simple non-condensing engine, running at speeds varying from about 85 to 145 rev. per

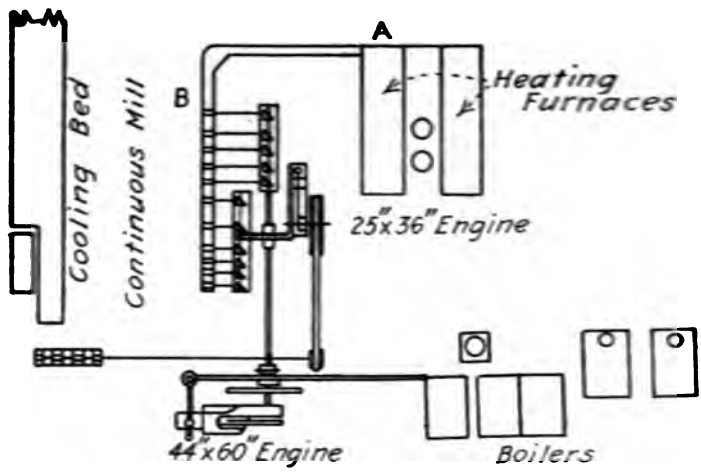


FIG. 1

min., the engine and mill speed being adjusted to suit the size of material rolled. Changes in roll speed were obtained by varying the engine speed, the engine governor being driven through friction disks, thereby allowing the engine speed to be readily changed.

The engine belt wheel was 218 in. (554 cm.) in diameter, the mill pulley 65 in. (165 cm.) in diameter, giving about 3.35 to 1 speed ratio, thus giving a speed range on the rolls from about 285 to 480 rev. per min. All four stands of rolls are used on this mill for practically all sizes; on certain sections, however, but two stands are used.

Steam for operating the engines was obtained from the

boiler plant shown in Fig. 1, consisting of two boilers equipped with chain grate stokers, and three hand-fired boilers. The other mill equipment consists of a rope-operated cooling bed, shears, scales and rod coiler.

The extreme speed range of 285 to 480 rev. per min. on the finishing stands of this mill is directly due to the inability to roll 1½-in. (38-mm.) rods at a higher speed than 300 rev. per min., or to secure sufficient tonnage of the small sizes without a higher speed, the large number of sizes rolled making impossible the ideal mill arrangement of a single-speed mill, rolling a practically constant-size product.

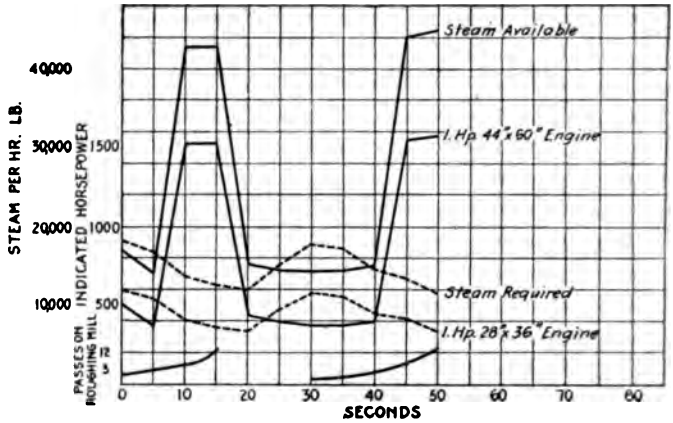
This mill was built a number of years ago, and has undergone a gradual increase in speed and output, until the capacity of the mill was fixed by the inability of the 28 by 36-in. (71 by 91-cm.) engine to stand further increase in speed or output. The maintenance of this engine and the mill belts was high and the over-all economy low. For these reasons it was decided to replace this engine by a larger and more powerful engine or some other type of drive. It was readily seen that an engine and belt-driven mill at a higher speed would not be desirable (the belt speed of the 28 by 36 in. engine being about 8000 ft. (2440 m.) per min. when rolling the small sections and it being impracticable to reduce the size of the mill pulley). An engine with a gear or rope drive had a higher first cost than a motor-driven mill, also a larger figured operating cost due principally to about 25 per cent higher coal cost at the mill than at the steel company's central power plant.

This mill presented some very interesting features: first, the different speeds required; second, the fact that the steel company had an a-c. turbine power plant with ample reserve capacity for driving the mill; and third, that the exhaust steam from the 44 by 60-in. (112 by 152-cm.) engine seemed to offer an ideal exhaust steam turbine location.

Tests were made on both mill engines in order to determine the power requirements of the finishing rolls and the exhaust steam available from the 44 by 60-in. engine, also the time relation between the power requirements of the finishing rolls and the steam supply from the 44 by 60-in. engine.

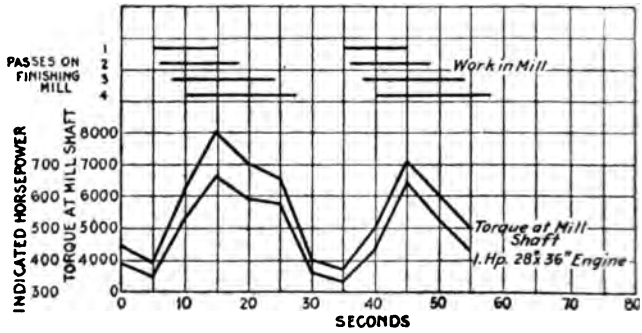
These tests were made by taking simultaneous continuous indicator cards on both engines, the mill speeds and the work in both mills being observed at the same time. Several tests on different sizes were made. The results of some of these tests are shown in Curves 1 to 19.

Curve 1 is for ⅜ in. (9.5 mm.) diameter round rods, and shows the horse power of each mill, also the exhaust steam available from the 44 by 60-in. engine, and the steam required by an exhaust steam turbine to drive the finishing rolls. These tests



CURVE 1—⅜-in. Rounds.

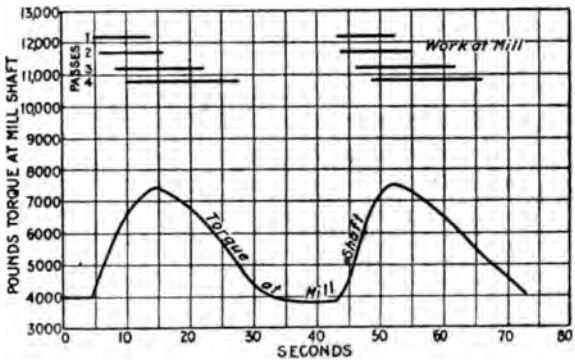
showed that sufficient steam was available, but that a small regenerator would probably be necessary. Tests on this size gave about 500 h.p. as the average power required and also showed a maximum mill speed of 472 rev. per min., and an



CURVE 2—⅜-in. Rounds.

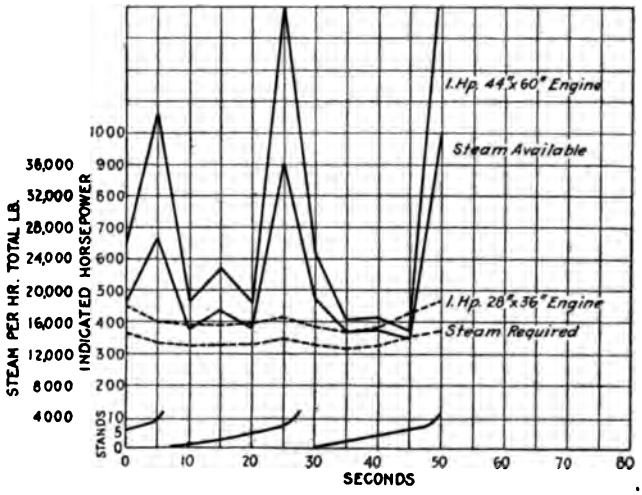
average speed of 462 rev. per min. Curve 2 is for a test of the 28 by 36-in. engine on this size. These tests show a peak torque of about 8000 lb. (3630 kg.). The maximum steam demands are greater than the minimum steam available; the periods of insufficient steam supply are extremely short. Curve 3 gives

the calculated duty cycle at the maximum mill output, the effective torque being 6000 lb. (2720 kg.), the h.p. 545, and the peak h.p. about 635.



CURVE 3—⅜-in. Rounds

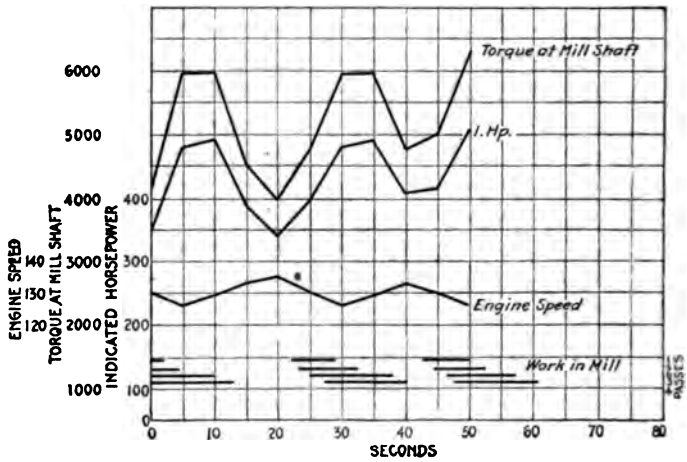
Curve 4 is for 29/64-in. (11.5-mm.) round steel rods, and shows an abundance of exhaust steam. The maximum mill speed on this size was 456 rev. per min. and the average about 442 rev.



CURVE 4—29/64-in. Rounds

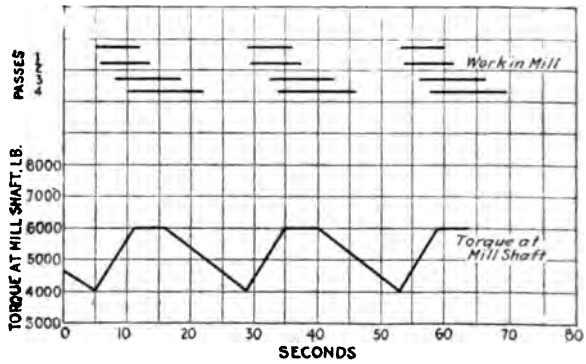
per min.; the r.m.s. horse power was 425. The peak torque was about 6000 lb. (2720 kg.), and the peak h.p. about 500. Curve 5 is for a test of the 28 by 36-in. engine on this size. Curve 6

gives the calculated duty cycle at the maximum mill output, the r.m.s. torque being 5400 lb. (2450 kg.), the h.p. 488, and the maximum horse power about 573.



CURVE 5—29/64-in. Rounds

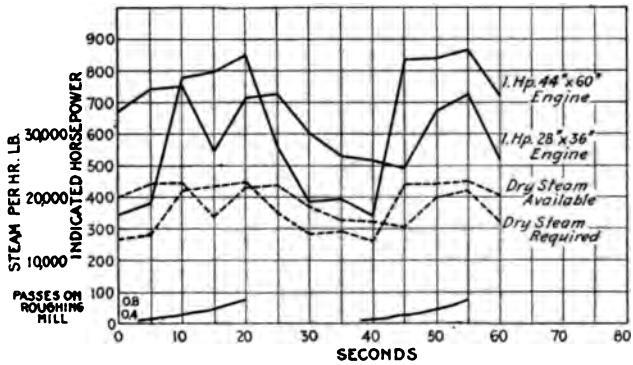
Curve 7 is for 47/64-in. (18.6-mm.) round rods, and shows the steam supply to be less than the steam required; this is due to but eight stands of roughing rolls on the continuous mill being used. This curve shows that in order to secure the best results



CURVE 6—29/64-in. Rounds

a mixed-pressure turbine and a small regenerator would no doubt be necessary. On this test the maximum mill speed was 448 rev. per min., the average 432 rev. per min., and the r.m.s. horse power 639. Curve 8 is for a test of the 28 by 36-in.

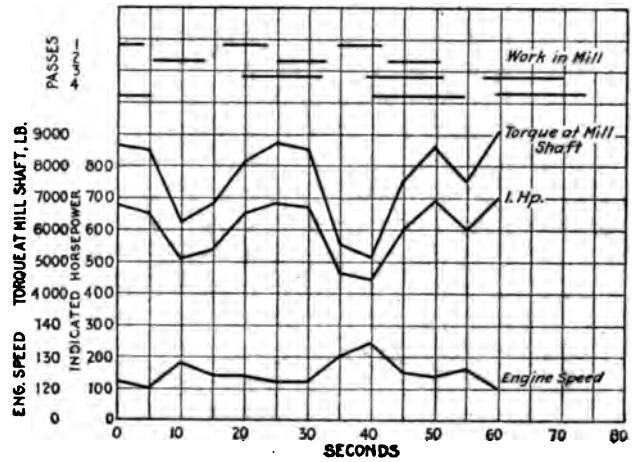
engine on this size. This test shows a maximum torque of 9300 lb. (4220 kg.), and a maximum h.p. of 740. Curve 9 gives the calculated duty cycle at the maximum mill output, the r.m.s.



CURVE 7—47/64-in. Rounds

torque being 8300 lb. (3760 kg.), the horse power 662, and the maximum horse power 780.

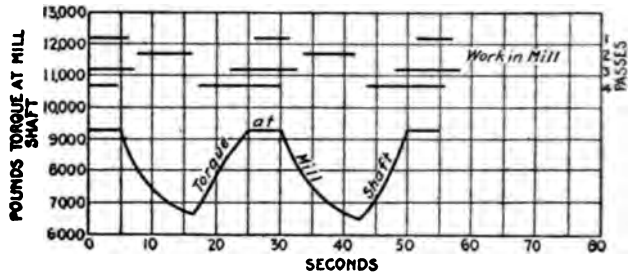
Curve 10 is for $\frac{7}{8}$-in. (22.2-mm.) round rods and shows that



CURVE 8—47/64-in. Rounds

the steam available is about equal to that required, but that a regenerator should be used. The maximum observed mill speed on this size was 382 rev. per min., and the average about 360 rev. per min., with a horse power of 510. Curve 11 is for

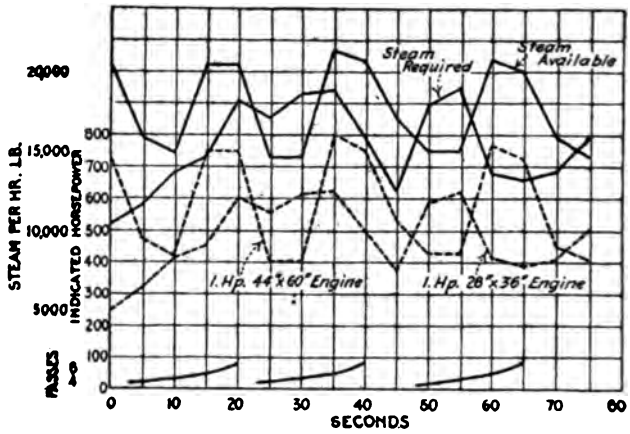
a test of the 28 by 36-in. engine on this size. The tests of this size show a maximum torque of nearly 10,000 lb. (4536 kg.) with about 650 horse power demand. Curve 12 gives the calculated duty cycle at the maximum mill output, the r.m.s.



CURVE 9—47/64-in. Rounds

torque being 8400 lb. (3810 kg.), the horse power 575, and the maximum horse power 650.

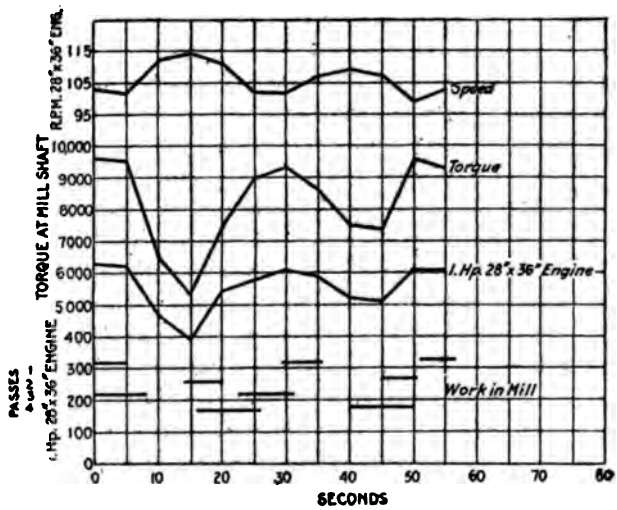
Curve 13 is for 63/64-in. (25-mm.) round rods and shows that the steam available exceeds the steam required. This is



CURVE 10—⅞-in. Rounds

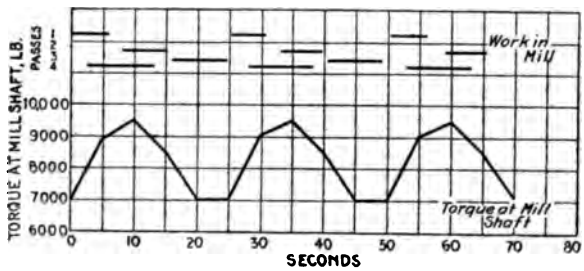
due to but two stands of finishing rolls being used. The maximum observed mill speed was 312 rev. per min., the average about 300 rev. per min., and the r.m.s. horse power 340. Curve 14 is for test No. 2, and Curve 15 for test No. 4 on this size. In test No. 2 both passes were in the mill at the same time,

resulting in very high peaks with long rest periods between, while in test No. 4 the two passes did not coincide. The total amount of work done, whether rolling is done with high peaks and long rest intervals, or low peaks and shorter rest periods,



CURVE 11—⅞-in. Rounds

is practically the same. In the calculated duty cycle for the maximum mill output (Curve 16), the peaks are taken on the basis of the two passes not occurring at the same time; this gives a cycle similar to test No. 4, the r.m.s. torque being 6800 lb.

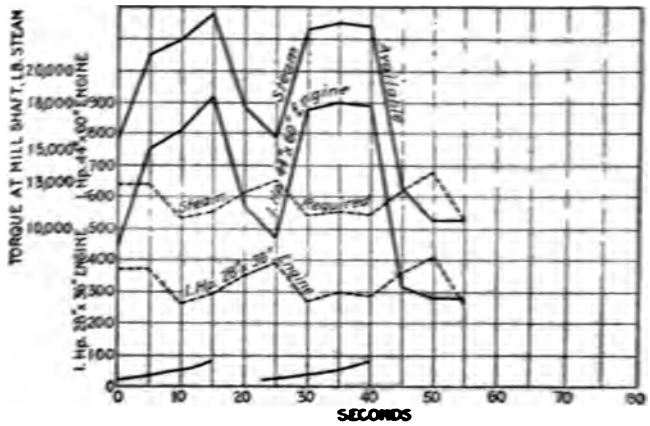


CURVE 12—⅞-in. Rounds

(3080 kg.), the horse power 414, the maximum torque 9800 lb. (4445 kg.), and the horse power 545.

Curve 17 is for 1¼-in. (31.7 mm.) round rods and shows the steam required to be in excess of the steam available. The

maximum observed mill speed was 314 rev. per min., the average being 285 rev. per min., and the horse power about 400. Curve 18 is for a test of the 28 by 36-in. engine on this size, and shows high peaks when passes one and three coincide. Curve



CURVE 13—63/64-in. Rounds

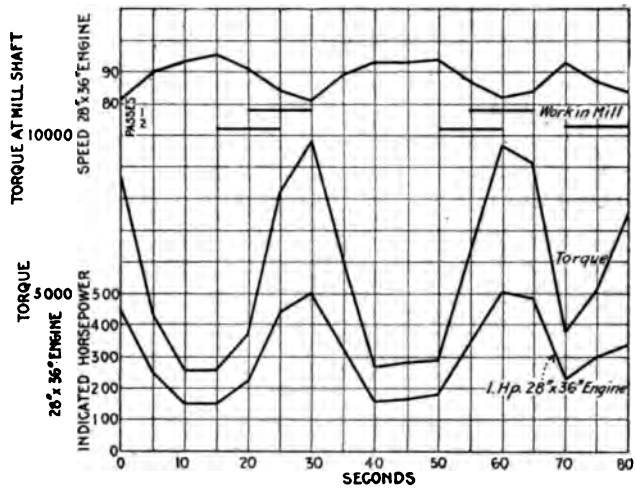
19 is the calculated torque to give maximum mill output and gives an effective torque of 7500 lb. (3400 kg.), with a horse power of 604, and a maximum horse power of 640.

A summary of the foregoing tests gives:

Diameter of Rod		Mill speed		Effective h.p.	Peaks h.p.	Lb. steam available	Lb. steam demanded	Mill speed desired
in.	mm.	max.	average					
3/8	9.5	472	462	500	669	25,300	14,900	475 - 480
29/64	11.5	456	442	425	509	21,200	13,500	475 - 480
47/64	18.6	448	432	639	738	18,250	19,100	420 - 435
7/8	22.2	382	360	510	635	17,600	15,300	360 - 375
63/64	25.0	312	300	340	506	18,400	10,250	305 - 310
1 1/4	31.7	314	285	400	600	10,500	13,000	285 - 300

The test results show that a large amount of exhaust steam would be lost if the low-pressure turbine were used for driving the finishing rolls direct. Also it was found that the low-pressure turbine would be wasteful of steam if the turbine speed varied with the mill speed. Gearing the turbine to the

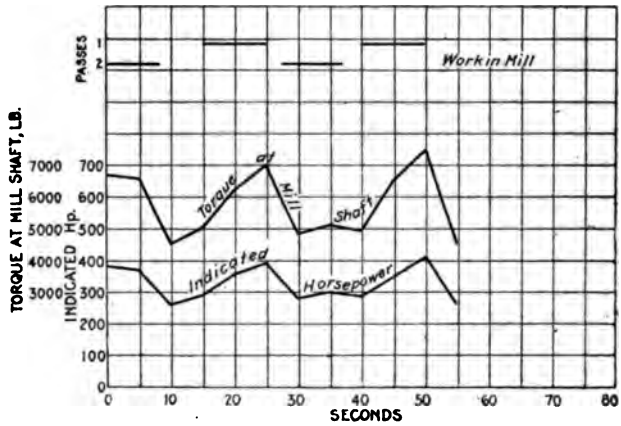
mill was not looked upon favorably, as the experience with several turbine gears on pump work had not been entirely satisfactory. Further objections to the turbine were the cost



CURVE 14—63/64-in. Rounds

of condensing water and the investment necessary for pumping equipment and pipe lines.

A careful consideration of the various drives resulted in the

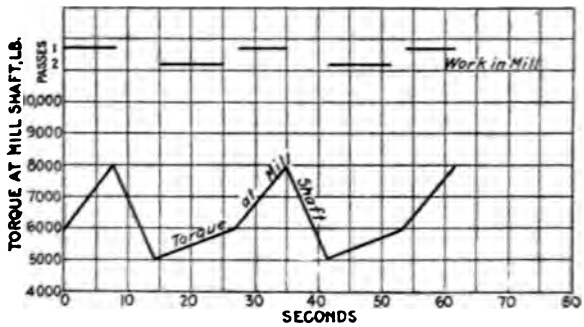


CURVE 15—63/64-in. Rounds

decision to install a motor drive, either a-c. or d-c., and obtain power from the steel company's central power plant. It was found that this would give an economical drive and be lower

in first cost than either a rope or geared engine. Also, the use of a motor would not interfere with the future installation of an exhaust steam turbine, which could operate in parallel with the company's power plant.

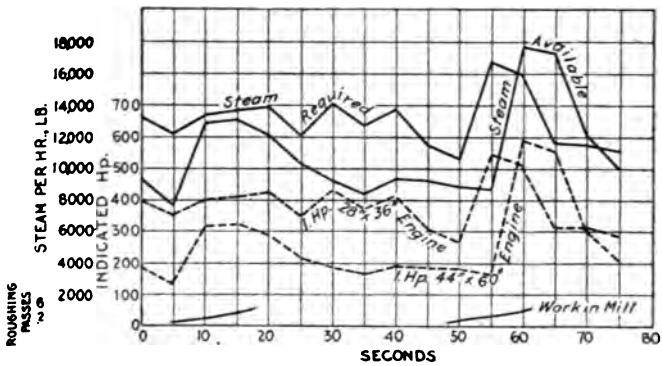
At this time, it may be of interest to state the reasons which



CURVE 16—63/64-in. Rounds

influenced the purchase of a concatenated motor instead of, first, a direct-current motor, or second, an induction motor operating with a speed-regulating set.

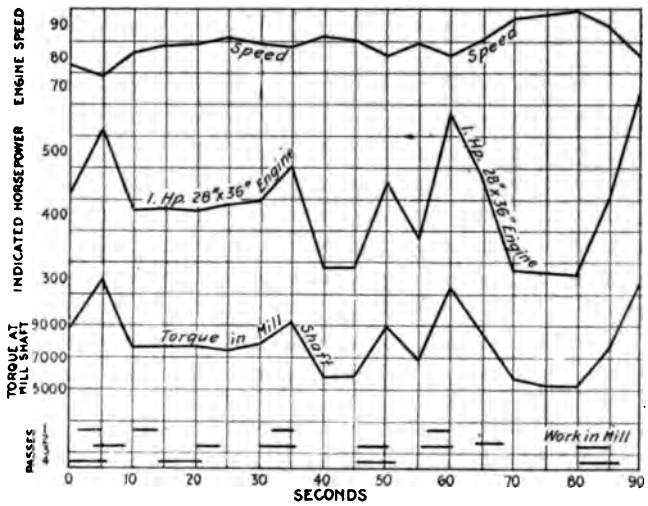
(1) The direct-current motor was entirely practical, but presented no advantages over the concatenated motor, except



CURVE 17—1¼-in. Rounds

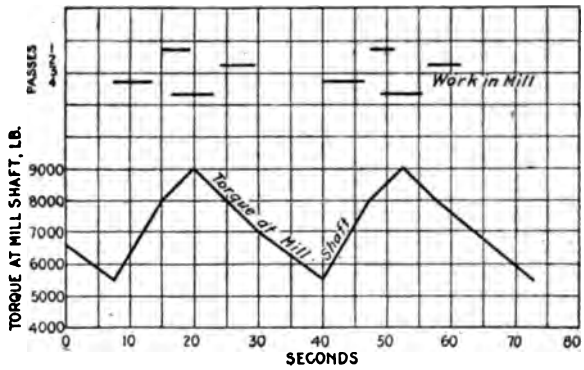
that smaller speed steps were possible. This was negligible because the concatenated set gave as many speeds as were necessary. The disadvantages of the direct-current motor were, that it was more expensive and, as it required a motor-generator set, less efficient.

(2) The speed-regulating set would have about the same or a slightly better efficiency than the concatenated motor, would be about the same in first cost and would have a higher power



CURVE 18—1¼-in. Rounds

factor at low speeds. Its disadvantage lay in the fact that a commutator motor or synchronous converter would be required. Little was known about the performance of a commutator motor



CURVE 19—1¼-in. Rounds

operating on the high frequency which would be obtained at this mill, commutator motors on mill work operating at frequencies around 20 cycles per second not being in satisfactory

service either here or abroad, and it is questionable if at the present time a guarantee for a satisfactory commutator motor could be obtained for the work of this mill.

Using a synchronous converter and a motor, or a motor-generator set, would not give as high efficiency as a concatenated set.

Both of these systems involved the use of commutators and would require more attention than the concatenated set. They also had the disadvantage of requiring a high mill speed before the reduced speeds could be obtained, whereas the motor installed has no regular attendant, and with the control as now adjusted, the motor starts, accelerates and drops into concatenation without exceeding the synchronous speed of the combined motors.

An attempt was made to limit the mill to two or three speeds. A 16-pole main and a 4- and 8-pole secondary motor would give poles and speeds as follows:

Main motor	Secondary motor	Both motors	Synchronous speed
16 poles	none	16 poles	450 rev. per min.
16 "	4 poles	20 "	360 "
16 "	8 "	24 "	300 "

This eliminated the 400-rev. per min. speed, which is one of the most important on the mill, about 40 per cent of the mill output being on this speed.

Changing to a 14-pole main motor would give 514, 400 and 327 rev. per min. This would give a dangerously high speed for the $1\frac{1}{4}$ and $1\frac{1}{2}$-in. (31.7 and 38-mm.) rods, and would also eliminate the 450-rev. per min. speed, which is important on some sizes.

Leaving the secondary motor unchanged, and placing a double winding on the main motor, gave all the speeds required. This resulted in a 4- and 8-pole secondary motor and a 14- and 16-pole primary motor. This combination gives the following speeds:

Main motor.	Secondary motor	Both motors	Synchronous speed
14 poles	none	14 poles	514 rev. per min.
16 "	"	16 "	450 "
14 "	4 poles	18 "	400 "
16 "	4 "	20 "	360 "
14 "	8 "	22 "	327 "
16 "	8 "	24 "	300 "

[OSCHMANN]

FIG. 2—2200-VOLT 600-H.P. CONCATENATED INDUCTION MOTOR SET ARRANGED TO OPERATE AT SIX SYNCHRONOUS SPEEDS, BUILT FOR OLIVER IRON AND STEEL COMPANY.

[OSCHMANN]

FIG. 4—SWITCHBOARD FOR PRIMARY AND SECONDARY CONTROL CIRCUITS OF SIX-SPEED CONCATENATED INDUCTION MOTOR.

All these speeds are obtained by direct concatenation; theoretically, speeds corresponding to 6, 8, 10 and 12 poles can also be obtained by differential concatenation.

It was decided to install this motor, the motor to consist of a double-wound main motor and single-wound secondary motor, the first or primary motor to be 14 and 16 poles and have a wound rotor, the second or secondary motor to have its winding arranged for 4- and 8-pole connection, its rotor to be of the squirrel cage type. Both stators were mounted on a common bed-plate and the rotors on a common shaft, resulting in the motor shown in Fig. 2.

The larger motor receives three-phase energy at 2200 volts, 60 cycles, on either a 14- or 16-pole stator winding. Both 14- and 16-pole windings lie in the same stator slots and have the same coil pitch and coil size. The coil connections of the 14-pole windings are brought out on one side of the frame, the coil connections for the 16-pole winding being on the opposite side, thus making the connections of either winding readily accessible. The windings on the rotor of this motor are similarly arranged. The six leads from the rotor windings are connected to six split bronze collector rings mounted on the shaft between the two motors. These rings can be easily renewed.

The small motor has a single stator winding which can be connected in either four- or eight-pole combination; the pole changing is accomplished by means of oil switches located on the motor control board. The rotor of this motor is of the squirrel-cage type and has electrically welded bars and end rings. The rotor bars are of sufficient cross-section to resist the action of centrifugal force and will not bend out and damage the stator winding, should they become detached from the end rings.

The floor space taken by the complete unit is 14 ft. 8 in. by 10 ft. 7 in. (4.47 by 3.22 m.), and the greatest height above the floor is 6 ft. 10 in. (2.08 m.). The rotors are 5 ft. 9 in. (1.75 m.) and 2 ft. 10 in. (86 cm.) in diameter respectively, mounted on a shaft 14 in. (35.6 cm.) in diameter. The general construction of the motor is heavy. The rotor spiders are of cast steel and the motor is built to stand reversing at full speed. The two bearings, each 8 by 20 in. (203 by 508 mm.), are self-aligning and of the ring-oiled type. The motor and mill are connected by a flexible coupling, the bearing next the mill and the coupling hub forming a thrust bearing. The brush holders for the col-

lector ring brushes can be removed and either stator slipped aside to give access to any part of the stator or rotor windings.

The motor was installed about where the mill pulley formerly was, the present mill plan being shown in Fig. 3.

For the operation of the motor no regular attendant is needed, as the changing of speeds is simple and requires no electrical knowledge or experience. The engineer on the 44 by 60-in. (112 by 152-cm.) engine attends to all speed changes and also

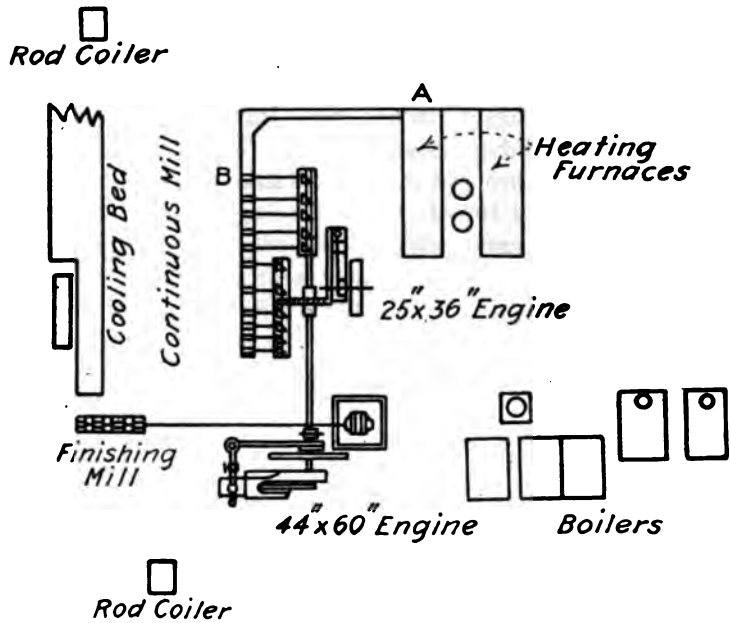


FIG. 3

starts and stops the motor. The controller for the motor is mounted adjacent to the throttle of the engine. In practise it has been found that, having the motor controller near the engine throttle, the engineer can handle both mills easily, the extra work and attention required being almost negligible.

The ease and simplicity in handling the mill is one of the best points in favor of the concatenated motor, as has been shown repeatedly in stopping the mill and backing out "stickers", or pieces caught in guides and refusing to go through rolls. The motor can be stopped, reversed and the sticking rod backed

out, the motor again stopped, restarted and immediately accelerated to full operating speed. This is generally done in time to roll the billets coming through the continuous mill and prevent their being scrapped. On several occasions this has taken place, the quick stop and start saving about a third of a ton of steel from becoming scrap. The total time of stopping, backing out, stopping and accelerating to operating speed, was less than a minute. The stopping and reversing was easily done, and no apparent strain or distress on motor or control was noticeable.

The control board for this motor is shown in Fig. 4. The wiring diagram is shown in Fig. 5. The choke coils, lightning arresters and disconnecting switches are mounted on the wall of the motor house and are connected to the control board through series transformers for wattmeter and overload relays to switch *A*. These transformers are connected in Z and give overload protection on all three phases.

Oil switch *A* is a triple-pole circuit breaker, having inverse-time-limit overload trip and low-voltage release, and is also provided with a magnetically operated lockout which prevents switch *A* from being closed unless both main line contactors *F* and *R* are open. This is provided to prevent the mill from starting should the engineer attempt to close switch *A* and not notice that the main line contactors had remained closed.

From switch *A*, current passes to the forward and reverse main line contactors *F* and *R*, one phase passing through a series transformer which operates the current-limit relays *CR* which control the resistance contactors.

F and *R* are three-pole, 2200-volt, magnetically operated air-break contactors. A mechanical and electrical interlock is provided between these contactors. The electrical interlock is not the conventional interlock disks working on the connections of the magnet coils, but consists of a small shunt transformer *TL* with its primary connected across one phase of the contactors as shown (Fig. 5). The secondary of the transformer operates the small contactor *L*. Contactors *F* and *R* have their operating circuit closed through contactor *L* or the interlock on *L*. As long as there is potential on the motor, contactor *L* will remain closed and thereby prevent either *F* or *R* from closing. As soon as *L* opens, either *F* or *R* can close, depending on the position of the master controller. This method of interlocking was deemed necessary, as the operation of the contactors is so

rapid that in reversing the motor, one contactor might close before the arc on the other was ruptured, and thereby produce a short circuit through the arc on the open contactor. The present arrangement has proved entirely satisfactory.

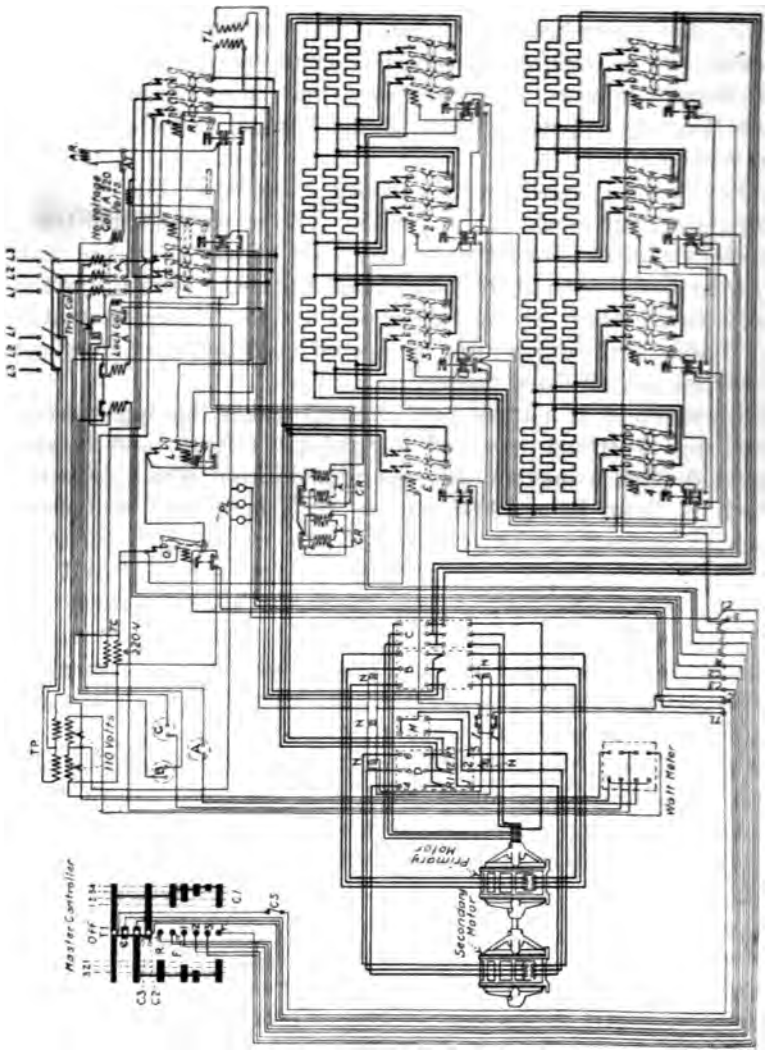


FIG. 6

The operation of the main line contactors shows that double-pole contactors would be as satisfactory as the triple-pole contactors installed. As the arcs, particularly the heavy arcs,

are always single-phase, switch *B* might also be double-pole instead of triple-pole.

From contactor *F* and *R*, current passes to oil switch *B*, where connection is made to either the 14- or 16-pole stator winding of the primary motor. Oil switch *B* is mechanically connected to oil switch *C*, so that *B* and *C* are operated by one handle. Switch *C* controls the rotor winding of the primary motor. Closing switch *B* on the 14-pole side will also close switch *C* on its 14-pole side. From switch *C* the current passes to a grid resistance mounted above the control board. This resistance is ample to reduce the mill speed to about 50 rev. per min. and hold it at this point for 15 to 20 minutes, the friction of the mill being the only load. This low speed is used to adjust the rolls and roll trial bars. The end of the resistance is either short-circuited by contactor *E* or the current passes into switch *D*, where it is directed into the stator of the secondary motor. Switch *D* is mechanically connected to switch *M*. These switches give either the 4- or 8-pole connection on the stator of the second motor. Closing switch *D* on the 1, 2 and 3 side gives a single-circuit eight-pole delta connection to the stator of the secondary motor; closing *D* on the 4, 5 and 6 side also closes switch *M* and gives a double-circuit four-pole star connection to the stator of the secondary motor. Switch *D* is provided with interlock switches *I* and connected to contactor *E* and arranged to close contactor *E* when switch *D* is open. To avoid having the mill try to accelerate from a concatenated to a direct speed should switch *D* open and thereby close contactor *E*, switch *D* is provided with a lock *N*, so that it cannot be opened or closed unless the master controller is placed on the off point and switch *A* is open. Switches *V* and *C* are provided with similar locks. The pilot lights *PL* indicate the position of the master controller; their circuit is closed when the controller is on the starting or running points. Current for the pilot lamps and small solenoids *N* which operate the locks on switches *A*, *B*, *C* and *D* is obtained from the potential transformers *TP*, and is independent of the position of switch *A*.

Contactors 1 to 7 are triple-pole low-voltage contactors and are arranged to short-circuit portions of the resistance; they are connected so that a contactor sticking or remaining closed will not produce dangerous currents in starting or reversing. These contactors are controlled by current from transformer *TC*, which is connected to the control side of switch *A*; current from the transformer passes through contactor *O* to current limit relays,

CR, which are set to close the contactors in regular sequence when the starting current drops to about full-load value. When operating on the 14- or 16-pole speeds, contactors 6 and 7 will remain open and give a 10 per cent slip at full load; by closing switch *R*6, contactor 6 will close and give a 5 per cent slip at full speed. Contactor 7 is always open on the 14- or 16-pole speed.

When operating on the concatenated speeds, contactor *E* is open and interlocks on *E* are closed, which allows contactors 6 and 7 to close, current limit the same as the remaining contactors, thereby leaving the motor without external resistance in the rotor circuit other than the resistance of the wires. Contactor *O* controls the current for all contactors except itself and contactor *L*. Contactor *O* is used to prevent the motor from starting upon the resumption of power in case of the failure of switch *A* to open should the power supply be interrupted. Contactor *O* opens on failure of power and can only be closed by placing the master controller in the off position.

The master controller is located about 80 ft. (24 m.) distant from the control board, and to guard against the master controller becoming inoperative, switch *CS*, located near the master controller, is provided. The action of switch *CS* is to open all the contactors and oil switch *A* and stop the motor should the master controller be out of order.

A test switch *AT* is provided on the control board which opens oil switch *A*. Resistance *AR* is connected across switch *AT* so that when switch *AT* is open, a slight current passes through the low-voltage release coil of switch *A*. This current is just sufficient to neutralize whatever residual magnetism may remain in the armature of the low-voltage release, and causes it to drop at once and open switch *A*.

It will be noted that the starting resistance is connected between the rotor of the main and the stator of the secondary motor. The circuit between the motors is established before the motors are started and the entire starting current passes through the secondary motor. This simplifies the control of the mill and makes the starting simple, as this method allows the mill to come directly to whatever speed the control is set for.

In stopping the mill, the master controller is usually placed in the off position, and the motor allowed to stop gradually. In emergency the motor can be reversed at full speed; in reversing on the concatenated speeds the secondary motor acts as a part of the circuit. The simplicity of this method is obvious.

The operation of this control is as follows:

Disconnecting switches are closed and power is on the lines. Master controller is on off point and oil switch *A* is open.

For Direct Speeds

Close switch *B* for either 14 or 16 poles. Close switch *A*. Closing switch *A* closes contactor *E* through interlock *L* on switch *D*. Contactor *O* also closes, its circuit being closed through segment *C* on master controller. After closing, *O* will remain closed regardless of position of the master controller, its holding circuit being established by the interlocks on *O*.

Starting. Placing the master controller on the first point closes either *F* or *R*; this puts potential on the main motor and closes contactor *L*. Placing the controller on the second point, contactor No. 1 can close. Placing the controller on the third point, contactor No. 2 can close. Placing the controller on the fourth point, contactor Nos. 3, 4, 5 can close. Contactor 6 can close if switch *R*6 is closed; contactor 7 cannot close as its closing circuit is open at contactor *E*. Under operating conditions the master controller is placed directly on the fourth or running point, and the contactors close in regular sequence at about full-load current, their control being the usual current limit type for a-c. contactors.

Reversing. When master controller is thrown from forward to reverse, contactor *R* will close as soon as arc on *F* is interrupted, and thereby open contactor *L*.

Concatenated Speeds

Oil switch *B* is placed on either the 14- or 16-pole connection. Switch *D* is closed for either 4- or 8-pole connection. Oil switch *A* is closed, when contactor *O* closes as before. Contactor *E* does not close, however, as its closing circuit is open at interlock *I* on switch *D*.

Starting, Running and Reversing. Exactly the same as for direct speeds, except that contactors 6 and 7 will close current limit the same as the rest of resistance contactors.

Summary

The control as used on this motor is more simple than a speed-regulating control in its operation, and is comparable with the magnetic control of a single-speed motor. The starting, stopping and reversing are as easily accomplished as if the motor were a single-speed motor. The only difference in handling is to operate switches *B* and *D* to secure the proper pole connection, and as this is generally done while changing rolls, it causes no delay or inconvenience. The only serious objection to the con-

catenated set is the low power factor on the concatenated speeds. The low power factor in this particular case has not been found serious. The power plant has a larger day than night load, so that the concatenated set working on the day shift reduces the power factor at the power plant but slightly. The lowest speeds, and therefore the lowest power factor, are generally obtained on the night shift. However, several synchronous motors (installed about five years ago), operate at reduced loads on the night shifts and it has been found that about 100 per cent power factor can be readily obtained at the power plant during the night, and 87 to 90 per cent during the day.

The criticism has been made that the control of concatenated motors is complicated: in reply to this, I would state that this motor has six definite speeds and two additional resistance speeds. Switches and contactors are provided to take care of these speeds and in addition the control has been further complicated in order to make the operation of the motor and control as fool-proof as possible, and thereby make unnecessary a special attendant at the mill.

The motor was installed in June, 1913; up to this time (April 1914) there have been only three mill interruptions, all of which were due to the control apparatus, as follows:

(1) An open circuit at interlock on contactor *F* which allowed low-voltage release to drop and open switch *A*. This interlock consists of a $\frac{1}{2}$-in. (12.7-mm.) copper rod pressing against a copper block contact; the copper rod is insulated and clamped to the contactor. The clamp became loose and allowed the rod to slip out and open the circuit.

(2) Defective low-voltage release coil on switch *A*.

(3) Burnt-out potential coil on one of the current-limit relays *CR*.

The total time lost due to these three interruptions was 68 minutes, and it will be noted that, excepting the first, not one of these interruptions was due to the design or type of the control, but rather to minor defects in manufacture. The motor has easily performed the work demanded of it, and the results obtained have justified the choice of this type of motor drive.

Should the same problem be presented for solution at this time, it would probably be solved in the same manner, notwithstanding the recent advances made in speed-regulating systems. It should also be noted that the ease of handling this motor and the ability to do without a trained operator make this type of motor extremely desirable.

DISCUSSION ON "CONCATENATED INDUCTION MOTORS FOR ROLLING MILL DRIVE" (OSCHMANN), DETROIT, MICH., JUNE 23, 1914.

Rudolph Tschentscher: The three points which stand out very prominently to me as a steel man are these: First, the exceptional reliability of the equipment—it entailed a loss of a little over one hour's time in practically a year's operation; second, the low operating cost, there being no additional attendance required; and third, probably greater than either of the other two, the rapidity of the control movement. I think the paper gives the time for braking, and reversing the forward motion, as being done within one minute. That, to one in the steel business, means a very considerable saving in tonnage.

T. E. Tynes: One of the experiences that probably all steel mill men have had, is that when you ask the management to put in new equipment, they come back to you with the argument "The first thing you will want is a spare unit to take care of that in case there is a breakdown." I am glad to note the reliability of this set Mr. Oschmann has just described. Probably it does not need a spare unit. I see no reason why, in the modern mill motor and the modern equipment the manufacturers are giving us, we cannot say we have as reliable apparatus as the steam engine.

A. E. Averrett: I would like to mention one feature in concatenated motors. In case of a small reduction in speed, such as 14 or 16 poles concatenated with 4 poles, the efficiency and power factor will remain quite high, but when a speed reduction to $\frac{1}{2}$ or thereabouts takes place the power factor is very much reduced due to the second motor drawing its current through the first motor; the output of both motors being approximately equal. With rheostatic control the power factor would remain high, but the efficiency would go down proportionally to the speed; with concatenated control the reverse takes place, that is, high efficiency, but power factor reduced approximately proportionally to speed. Therefore, large speed reduction by concatenation is at the expense of power factor.

Presented at the 31st Annual Convention of the American Institute of Electrical Engineers, Detroit, Mich. June 24, 1914, under the auspices of the Electrophysics Committee.

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THE SPHERE GAP AS A MEANS OF MEASURING HIGH VOLTAGE

BY F. W. PEEK, JR.

ABSTRACT OF PAPER

A gap method of measuring high voltage is desirable in certain tests because a gap measures the maximum point of the voltage wave.

The needle gap is unreliable, and is subject to large corrections due to humidity, etc. The sphere gap is free from complicated corrections and the curve is subject to calculation. Wherever voltage is measured by a gap, correction must be made for air density—that is, altitude or barometric pressure, and temperature. The laws for this correction have been deduced for the sphere gap, from tests, over an air density range equivalent to that from sea level to 18,000 ft. elevation. An equation is given for calculating sphere spark-over curves for various spacings, radii, air density, etc.

Standard measured curves for convenient sizes of spheres at sea level are given for practical use, as well as a table for applying these curves to any altitude. The altitude correction may be made very accurately to the standard curve, either by applying the calculated correction constant or by applying the correction factor given in the tables.

The complete standard curves should not be calculated when reliable measured curves are available.

The effects of high frequency and impulse voltages are discussed. In making measurements certain precautions are necessary for accuracy, as well as for protection of apparatus. These precautions are discussed and test results are given.

A GAP method of measuring high voltages is often desirable in certain commercial and experimental tests. As a gap measures the maximum point of the voltage wave it is therefore used in many insulation tests where breakdown also depends upon the maximum voltage point. In most commercial tests an accuracy of one or two per cent is sufficient. A greater accuracy can be obtained with the sphere gap for special work where proper precautions are taken.

THE NEEDLE GAP

The needle gap is unreliable at high voltages because, due to the brush discharge and broken-down air that precedes the spark-over, variations are caused by humidity, oscillations, and frequency.[1]

The needle gap is also inconvenient because needles must be

1. Discussion, F. W. Peek, Jr., TRANS. A. I. E. E., Vol. XXXII, 1913, p. 812. *G. E. Review*, May, 1913.

replaced after each discharge; the gap becomes very long at high voltages, and the calibration varies somewhat with the sharpness of the needle.

The effect of humidity is shown in Fig. 1, where it can be seen that a higher voltage is required to spark over a needle gap when the humidity is high than when it is low. (Curves of Fig. 1 are intended only to illustrate this effect and not for use in making accurate measurements). It is probable that the corona streamers in humid air cause a " fog ", and then agglomerate the water particles, which, in effect, increase the size of the electrodes.

All spark curves of whatever form of gap must be corrected for air density; that is, altitude and temperature. For *low voltages* the spark-over voltage of the needle gap decreases approximately as the air density. At higher voltages the effect becomes erratic, probably due to humidity.

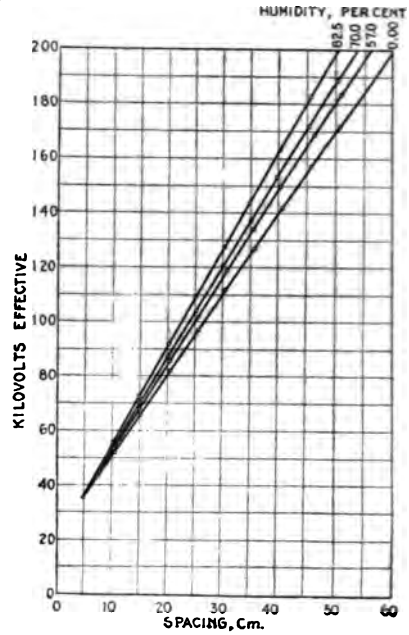

FIG. 1—APPROXIMATE NEEDLE GAP CURVES FOR DIFFERENT RELATIVE HUMIDITIES

THE SPHERE GAP

The voltage required to spark over a given gap between spheres increases with the diameter of the sphere. Corona cannot form on spheres, or rather, the spark-over point and corona point are coincident if the spacing is not greater than the diameter of the sphere. Practically a spacing as great as three times the radius may be used without appreciable corona. The voltage limit of a given sphere in high-voltage measurements is thus reached when a gap setting greater than three times the radius is required. A larger sphere should then be used.* With this space limit, the first evidence of stress is complete spark-over; corona can never form, and all of the undesirable effects and variables due to brush

*More accurate and consistent results are obtained, however, for spacings less than 2 R.

discharge and broken-down air are eliminated. Humidity has no appreciable effect.

The space factor is relatively small. Several thousand measurements may be made without repolishing. The curve may be calculated. The only correction is the air density correction. This has been investigated and the results are given below. The correction is quite simple. Fig. 2 gives typical sphere-gap curves for both spheres insulated and for one sphere grounded. Tables I to V give spark-over curves for 6.25-, 12.5-, 25-, 50- and 100-cm. spheres at sea level (25 deg. cent., 76 cm. barometer). $\delta = 1$. (See Note 2).

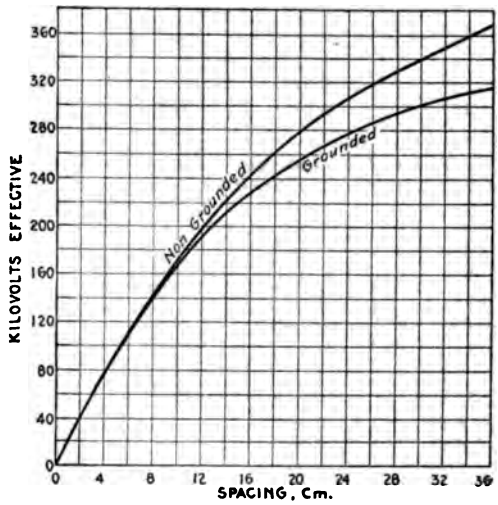

FIG. 2—SPARK-OVER CURVES
25 cm. diam. spheres

Calculation of Curves: The gradient or stress on the air at the sphere surface, where it is greatest, is found mathematically:

$$g = \frac{e}{x} f \text{ kv. per cm.}$$

where e is the applied voltage in kilovolts, x is the spacing in centimeters, f is a function of $\frac{x}{R}$, and R is the radius of the sphere in centimeters.

2. *The Calibration of the Sphere-Gap Voltmeter*, Chubb and Fortescue, TRANS. A.I.E.E., Vol. XXXII, 1913, p. 739. Discussion by F.W. Peek, Jr., p. 812. "The Sphere Gap as a Means of Measuring High Voltage," F. W. Peek, Jr., *G. E. Review*, May, 1913.

The *average* gradient between these limits of separation is[4]

$$g_s = 27.2 \left(1 + \frac{0.54}{\sqrt{R}}\right) \text{kv. per cm. max.} \qquad (1a)$$

$$g_s = 19.3 \left(1 + \frac{0.54}{\sqrt{R}}\right) \text{kv. per cm. eff. sine wave.} \qquad (1b)$$

TABLE IV

SPHERE-GAP SPARK-OVER VOLTAGES.
50-cm. DIAMETER SPHERES

Spacing		Kilovolts effective	
cm.	in.	Non-grounded	Grounded
		*	
2	0.787	40	40
4	1.575	76.5	76
6	2.362	115.5	112
8	3.150	149	145
10	3.937	189	185
12	4.72	224.3	220
14	5.51	255.5	250
16	6.30	285	275
20	7.87	335	320
25	9.83	393	377†
30	11.81	445	420
35	13.80	493	456
40	15.75	537	489
45	17.72	573	516
50	19.19	605	541
55	21.65	633	561
60	23.62	660	579
65	25.60	684	594
70	27.56	705	608
75	29.55	725	619

*These values are calculated.
†Spacings above 22 cm. are calculated.

The maximum variation from the average between the limits may be 2 per cent. When x is less than $0.54\sqrt{R}$, g_s increases very rapidly because the spacing is then less than the "rupturing energy distance."[5] Above $x = 3R$, g_s apparently gradually increases[5]. This increase seems only apparent and due to the

4. See *Law of Corona III*, F. W. Peek, Jr., TRANS. A. I. E. E., Vol. XXXII, 1913, p. 1767.
5. Ibid.

shanks, surrounding objects, etc., better distributing the flux or lessening the flux density. When *both spheres are insulated* and of practical size, the change is not great within the prescribed limits. When *one sphere is grounded*, however, this apparent increase of gradient is very great if the mathematical f, which does not take account of the effect of surrounding objects, is used. For this reason this f_0 was determined experimentally, for the grounded case, by assuming g_s constant within the limits,

TABLE V

SPHERE-GAP SPARK-OVER VOLTAGES.

100-cm. DIAMETER SPHERE.

Spacing		Kilovolts effective	
cm.	in.	Non-grounded	Grounded
1.0	0.394	20	20
3.0	1.181	60	60
5.0	1.969	100	100
10.0	3.937	195	195
15.0	5.91	283	280
20.0	7.87	364	360
30.0	11.81	520	505
40.0	15.75	650	615
50.0	19.69	770	730
60.0	23.62	870	810
70.0	27.56	956	895
80.0	31.50	1044	956
90.0	35.43	1107	1010
100.0	39.37	1182	1057
110.0	43.35	1238	1090
120.0	47.20	1290	1133
130.0	51.20	1335	1160
140.0	55.70	1378	1189
150.0	59.10	1412	1212

These values are calculated.

as it is in the non-grounded case, and finding values of f_0 corresponding to the different values of $\frac{x}{R}$. These measurements were made with the grounded sphere 4 to 5 diameters above ground. Any given value of the ratio $\frac{x}{R}$ should require a constant f_0 to keep g_s constant independent of R. This was found to check.

The curves may be quite closely calculated thus:

$$e_s = g_s \frac{x}{f} \text{ (non-grounded) effective sine wave.} \qquad (2)$$

$$e_s = g_s \frac{x}{f_0} \quad \text{(grounded) effective sine wave} \tag{3}$$

where g_s is calculated from equation (**1b**), and f_0 or f is found from the table for the given $\frac{x}{R}$. *Curves need be calculated only when standard measured curves cannot be obtained.* Measured curves are given here. The average error, however, for curves calculated from the above equations, for 2-cm. diameter spheres and over, should not be greater than 2 or 3 per cent. The accuracy of calculations is not as great as in the case of the starting point of corona on wires.

TABLE VI

SPHERE-GAP GRADIENT FACTOR.

$\frac{X}{R}$	Non-grounded. Mathematical and actual practical coefficient* f	One sphere grounded. Actual practical coefficient f_0	One sphere grounded. Mathematical coefficient not correct on account of effect of shanks, etc. f_1
0.1	1.034	1.034	1.050
0.3	1.103	1.105	1.162
0.5	1.175	1.180	1.280
1.0	1.366	1.410	1.620
1.5	1.568	1.675	2.000
2.0	1.781	1.965	2.415
2.5	2.002	2.27	2.85
3.0	2.225	2.59	3.30
3.5	2.455	2.90	3.76
4.0	2.686	3.20	4.23

*Non-grounded: $f = \frac{1}{4}\left(\frac{X}{R} + 1 + \sqrt{\left(\frac{X}{R} + 1\right)^2 + 8}\right)$

One sphere grounded: $\begin{cases} f_0 = \text{experimental values.} \\ f_1 = \frac{1}{2}\left(\frac{X}{R} + \sqrt{\left(\frac{X}{R}\right)^2 + 4}\right) \end{cases}$

f_1 should not be used—see note above. f_0 should be used for the grounded case. The experimental values were determined with the grounded sphere four to five diameters above ground.

EFFECT OF AIR DENSITY OR ALTITUDE AND TEMPERATURE

We have found that the average gradient for various air densities may be expressed

$$g_s = 27.2\,\delta\left(1 + \frac{0.54}{\sqrt{\delta R}}\right) \text{ kv. per cm. max.}$$

$$g_s = 19.3\,\delta\left(1 + \frac{0.54}{\sqrt{\delta R}}\right) \text{ kv. per cm. effective}$$

where δ is the relative air density

$$\delta = \frac{3.92\,b}{273+t}$$

b = barometric pressure in cm.
t = temperature in deg. cent.

The standard sea-level curves correspond to 76 cm. barometric pressure and 25 deg. cent. or where $\delta = 1$.

Correction Factor. The standard curve may be made to apply to any given altitude by multiplying the voltage at different spacings by the correction factor, thus:

$$e_1 = e\left\{\frac{19.3\,\delta\left(1 + \frac{0.54}{\sqrt{\delta R}}\right)}{19.3\left(1 + \frac{0.54}{\sqrt{R}}\right)}\right\}$$

$$= e\,\delta\,\frac{\left(1 + \frac{0.54}{\sqrt{\delta R}}\right)}{\left(1 + \frac{0.54}{\sqrt{R}}\right)} = e\,k \qquad (4)$$

Practical Application. In order to avoid the trouble of calculating in practise, the factor is tabulated in Tables VII and VIII. This correction is very accurate. Table VII gives the correction factor for different sizes of spheres at different barometric pressures and at constant temperature. When volt-

TABLE VII

Approximate corresponding altitude ft.	Barometer		Values of k at 25 deg. cent. for standard spheres of the following diameters. Centimeters.						
	cm. Hg	in. Hg	6.25	12.5	25	37.5	50	75	100
0	76.00	29.92	1.000	1.000	1.000	1.000	1.000	1.000	1.000
500	74.58	29.36	0.981	0.980	0.980	0.979	0.979	0.979	0.979
1,000	73.14	28.79	0.964	0.963	0.962	0.961	0.960	0.960	0.960
1,500	71.77	28.25	0.948	0.946	0.945	0.944	0.943	0.942	0.942
2,000	70.42	27.72	0.932	0.929	0.927	0.926	0.925	0.924	0.924
2,500	69.09	27.20	0.916	0.913	0.911	0.909	0.908	0.907	0.907
3,000	67.74	26.67	0.902	0.899	0.897	0.895	0.893	0.892	0.891
3,500	66.51	26.18	0.887	0.884	0.882	0.880	0.878	0.876	0.875
4,000	65.25	25.69	0.873	0.870	0.867	0.865	0.863	0.861	0.860
4,500	64.01	25.23	0.859	0.855	0.852	0.850	0.848	0.846	0.845
5,000	62.79	24.72	0.845	0.841	0.838	0.835	0.833	0.831	0.830
6,000	60.45	23.80	0.817	0.812	0.808	0.805	0.803	0.801	0.800
7,000	58.22	22.93	0.791	0.786	0.782	0.779	0.776	0.774	0.772
8,000	56.03	22.05	0.765	0.759	0.754	0.750	0.748	0.746	0.744
9,000	53.84	21.20	0.739	0.733	0.728	0.724	0.721	0.719	0.717
10,000	51.85	20.41	0.716	0.709	0.703	0.698	0.694	0.692	0.690
12,000	48.09	18.93	0.669	0.661	0.656	0.651	0.647	0.644	0.642
15,000	42.88	16.88	0.606	0.596	0.589	0.585	0.580	0.577	0.575

ıge strikes across a given gap, its value, e_1, may be found by tak-
ng the voltage e, corresponding to the gap, from the standard
:urve and multiplying by the correction factor k, or a curve may
ɔe plotted corresponding to a given barometric pressure, thus

$$e_1 = ek.$$

TABLE VIII

Calculated values of k for different values of δ

$$k = \delta \left\{ \frac{1 + \dfrac{0.54}{\sqrt{\delta R}}}{1 + \dfrac{0.54}{\sqrt{R}}} \right\}$$

$$= \sqrt{\delta}\, \frac{\sqrt{\delta R} + 0.54}{\sqrt{R} + 0.54}$$

Relative air density	Values of k. Diameter of standard spheres in cm.						
δ	6.25	12.5	25.	37.5	50.	75.	100.
0.50	0.547	0.535	0.527	0.522	0.519	0.519	0.516
0.55	0.594	0.583	0.575	0.570	0.567	0.565	0.564
0.60	0.640	0.630	0.623	0.618	0.615	0.613	0.612
0.65	0.686	0.677	0.670	0.665	0.663	0.661	0.660
0.70	0.732	0.724	0.718	0.714	0.711	0.709	0.708
0.75	0.777	0.771	0.766	0.762	0.759	0.757	0.756
0.80	0.821	0.816	0.812	0.809	0.807	0.805	0.804
0.85	0.866	0.862	0.859	0.857	0.855	0.854	0.853
0.90	0.910	0.908	0.906	0.905	0.904	0.903	0.902
0.95	0.956	0.955	0.954	0.953	0.952	0.951	0.951
1.00	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1.05	1.044	1.045	1.046	1.047	1.048	1.049	1.049
1.10	1.090	1.092	1.094	1.095	1.096	1.097	1.098

Table VIII gives the correction factor for various values of δ.
The value of δ may be calculated for the given temperature and
ıarometric pressure, and a correction factor then found from the
able. Fig. 3 gives the standard curve for the 12.5-cm. sphere
non-grounded, 25 deg. cent., 76 cm. bar. pressure) and curves
alculated therefrom for 25 deg. cent. and various barometric
ıressures.

$$e_s = g_s \frac{x}{f_0} \quad \text{(grounded) effective sine wave} \tag{3}$$

where g_s is calculated from equation (1b), and f_0 or f is found from the table for the given $\frac{x}{R}$. *Curves need be calculated only when standard measured curves cannot be obtained.* Measured curves are given here. The average error, however, for curves calculated from the above equations, for 2-cm. diameter spheres and over, should not be greater than 2 or 3 per cent. The accuracy of calculations is not as great as in the case of the starting point of corona on wires.

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Practical Application. In order to avoid the trouble of calculating in practise, the factor is tabulated in Tables VII and VIII. This correction is very accurate. Table VII gives the correction factor for different sizes of spheres at different barometric pressures and at constant temperature. When volt-

Experimental Determination of Air Density Correction

Tests. The equation (4) for the air density correction factor was determined by an extensive investigation of the spark-over of spheres in a large wooden cask arranged for exhaustion of air. This cask was built of paraffined wood and was 2.1 meters high by 1.8 meters inside diameter.

Tests were made by setting a given size of sphere at a given spacing, gradually exhausting the cask, and reading spark-over voltage at intervals as the air pressure was changed. (Temperature was always read, but varied only between 16 deg. and 21 deg. cent). This was repeated for various spacings on spheres ranging in diameter from 2.0 cm. to 25 cm. At the start, the

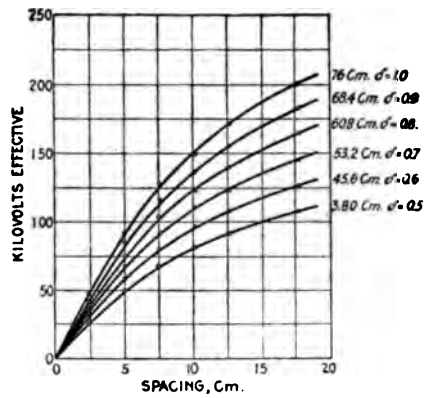

Fig. 3—Sphere Gap Spark-Over Voltage at Various Air Pressures

Temperature 25 deg.cent. 12.5-cm. spheres. Non-grounded. Drawn curves calculated. 76 cm. is standard curve. Points are from curves through measured values.

possible effect of spark-overs on the succeeding ones in the cask was investigated and found to be nil or negligible. A resistance of one to four ohms per volt was used in series with the spheres. Wave shape was measured and corrected for. Voltage was read on a voltmeter coil, by step-down transformer, and by ratio. Precautions were taken as noted in the discussion referred to below.[6]

In order to illustrate the method of recording data, etc., a small part of the data for various spheres and spacings is given in Tables IX to XVIII. Numerous data are plotted in curves,

6. *The Calibration of the Sphere-Gap Voltmeter*, Trans. A.I.E.E., Vol. XXXII, 1913, p. 739. Discussion by F. W. Peek, Jr., p. 812.

TABLE IX

SPHERE-GAP SPARK-OVER VOLTAGES AND GRADIENTS

2.54-cm. DIAMETER SPHERES—NON-GROUNDED.

Spacing cm.	Spacing in.	Temp deg. cent.	Press. in. of Hg	Relative air density	kv. eff.	kv. max.	g_s eff. measured	g_s max. measured
0.635	0.25	15	29.78	1.028	15.7	22.2	29.2	41.3
			28.63	0.99	15.3	21.65	28.5	40.3
			27.73	0.957	14.9	21.1	27.7	39.2
			26 93	0.93	14.4	20.4	26.8	23.0
			25.93	0.895	14.0	19.8	26.0	36.8
			24.68	0.852	13.6	19.2	25.3	35.7
			23.63	0.818	13.2	18.7	24.6	34.8
			22.38	0.776	12.5	17.2	23.25	32.0
			21.58	0.745	12.1	17.1	22.5	31.8
			20.78	0.717	11.8	16.7	22.0	31.1
			19.88	0.686	11.3	16.0	21.0	29.8
			18.78	Q.649	10.75	15.2	20.0	28.3
			17.88	0.618	10.4	14.7	19.35	27.4
			16.68	0.576	9.8	13.85	18.25	25.8
			15.73	0.544	9.26	13.1	17.2	24.4
			14.48	0.500	8.66	12.25	16.1	22.8

Barometer 29.78 in.

TABLE X

SPHERE-GAP SPARK-OVER VOLTAGES AND GRADIENTS

2.54-cm. DIAMETER SPHERES—NON-GROUNDED.

Spacing cm.	Spacing in.	Relative air density	kv. eff.	kv. max.	g_s eff. measured	g_s max. measured
3.81	1.5	1.01	52.4	74.2	29.2	41.4
"	"	0.962	50.5	71.5	28.1	39.8
"	"	0.923	49.1	69.5	27.4	38.7
"	"	0.875	45.7	64.6	25.5	36.0
"	"	0.834	45.2	64.0	25.2	35.7
"	"	0.798	42.8	60.6	23.8	33.8
"	"	0.757	41.3	58.5	23.0	32.6
"	"	0.734	40.4	57.2	22.5	31.9
"	"	0.722	39.0	55.1	21.7	30.7
"	"	0.669	38.0	53.8	21.2	30.0
"	"	0.629	35.6	50.4	19.8	28.1
"	"	0.590	34.1	48.3	19.0	26.9
"	"	0.551	32.7	46.3	18.2	25.8
"	"	0.527	31.2	44.3	17.4	24.7
"	"	0.487	30 5	43.2	17.0	24.1

TABLE XV

SPHERE-GAP SPARK-OVER VOLTAGES AND GRADIENTS.

12.5-cm. DIAMETER SPHERE—NON-GROUNDED.

Spacing cm.	Spacing in.	Relative air density	kv. eff.	kv. max.	g_s eff. measured	g_s max. measured
12.7	5	0.982	163.0	230.0	23.1	32.7
"	"	0.951	156.	221.0	22.2	31.4
"	"	0.917	150	212.5	21.3	30.2
"	"	0.88	147	208	20.9	29.5
"	"	0.846	143.5	203	20.4	29.8
"	"	0.807	139.5	197.5	19.8	28.0
"	"	0.78	134.5	190	19.1	27.0
"	"	0.736	131	185.5	18.6	26.3
"	"	0.699	125	177	17.7	25.1
"	"	0.666	120.5	170	17.1	24.2
"	"	0.637	115.5	163	16.4	23.1
"	"	0.598	109.5	155	15.5	22.0
"	"	0.561	104.5	147.5	14.8	21.0
"	"	0.541	101	142.5	14.3	20.2

TABLE XVI

SPHERE-GAP SPARK-OVER VOLTAGES AND GRADIENTS

12.5-cm. DIAMETER SPHERES—NON-GROUNDED.

Spacing cm.	Spacing in.	Relative air density	kv. eff.	kv. max.	g_s eff. measured	g_s max. measured
20.32	8	0.938	198.5	281	23.0	32.6
"	"	0.912	197	279	22.9	32.4
"	"	0.874	189.5	268	22.0	31.1
"	"					
"	"	0.842	183	259	21.2	28.9
"	"	0.804	176.5	250	20.5	29.0
"	"	0.767	169	239	19.6	27.8
"	"					
"	"	0.737	163.5	231	19.0	26.8
"	"	0.704	157.5	223	18.3	24.7
"	"	0.674	151	235	17.5	24.8
"	"					
"	"	0.615	140.0	198.0	16.2	23.0
"	"	0.568	130.5	184.5	15.1	21.4
"	"	0.528	120.5	171	14.0	19.8
"	"					
"	"	0.488	110	157	12.8	18.2
		0.464	105.5	149	12.2	17.3

TABLE XVII

SPHERE-GAP SPARK-OVER VOLTAGES AND GRADIENTS

12.5-cm. DIAMETER SPHERE—GROUNDED.

Spacing cm.	Spacing in.	Relative air density	kv. eff.	kv. max.	g_s eff. measured	g_s max. measured
6.35	2.5	0.908	95.5	135	21.2	30.0
		0.869	92.5	130.5	20.5	29.0
		0.828	88.6	125	19.7	27.8
		0.796	85.8	121	19.05	26.9
		0.758	81.1	114.5	18.0	25.4
		0.723	78.2	110.5	17.35	24.5
		0.69	73.2	103.5	16.25	23.0
		0.653	71.5	101	15.9	22.4
		0.62	68.2	96.3	15.15	21.4
		0.582	64.3	90.9	14.25	20.2
		0.539	60.7	85.8	13.5	19.05
		0.439	55.6	78.5	12.35	17.4

TABLE XVIII

SPHERE-GAP SPARK-OVER VOLTAGES AND GRADIENTS.

25-cm. DIAMETER SPHERE—NON-GROUNDED.

Spacing cm.	Spacing in.	Relative air density	kv. eff.	kv. max.	g_s eff. measured	g_s max. measured
7.62	3	1.018	139	196.5	22.2	31.5
		0.978	133.5	189	21.4	30.3
		0.942	129.5	183	20.8	29.3
		0.906	126	178	20.2	28.5
		0.888	121.5	172	19.5	27.6
		0.839	115	163	18.4	26.1
		0.796	111	157	17.8	25.2
		0.752	105.5	149	16.9	23.9
		0.718	101.5	142	16.3	22.7
		0.685	96.2	136	15.4	21.8
		0.646	91.5	129.5	14.6	20.7
		0.608	87.0	123	13.9	19.7
		0.570	81.3	115	13.0	18.4
		0.527	74.7	105.5	12.0	16.9
		0.491	70.8	100	11.3	16 0

Figs. 4 to 8. The points are measured values. The drawn lines are calculated by multiplying the voltage values from the standard curves at $\delta = 1$, by the correction factor k.

$$k = \delta \frac{\left(1 + \frac{0.54}{\sqrt{\delta R}}\right)}{\left(1 + \frac{0.54}{\sqrt{R}}\right)}$$

The calculated values check the measured values very closely.

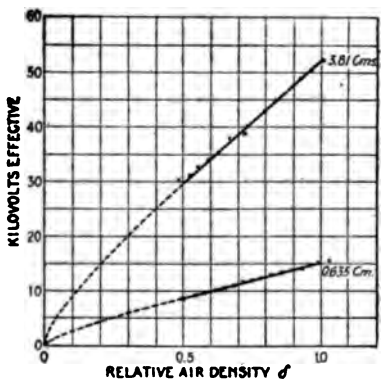

FIG. 4—SPARK-OVER VOLTAGE WITH VARYING AIR DENSITIES
2.54-cm. (1-in.) spheres. Non-grounded. Spacing 3.81 cm. (1.5 in.), 0.635 cm. (0.25 in.)

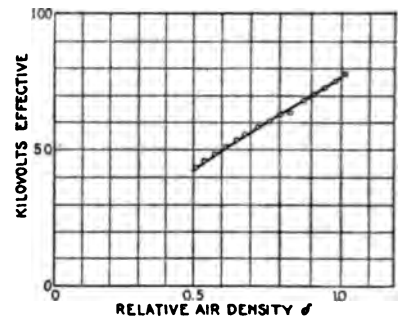

FIG. 5—SPARK-OVER VOLTAGE WITH VARYING AIR DENSITIES
5.08-cm. (2-in.) spheres. Non-grounded. Spacing 5.08 cm. (2 in.).

The equation for the correction factor was deduced from measured values as follows:

From a former investigation[7] it was found that at $\delta = 1$ the average gradient

$$g_s = g_0\left(1 + \frac{0.54}{\sqrt{R}}\right) \tag{1}$$

From the present investigation it was found that the average gradient at various values of δ is

$$g_s = g_0\,\delta\left(1 + \frac{0.54}{\sqrt{\delta R}}\right)$$

7. *Law of Corona III.* F. W. Peek, Jr., TRANS. A.I.E.E., Vol. XXXII, 1913, p. 1767. Discussion, TRANS. A.I.E.E., Vol. XXXII, 1913, p. 812.

The average measured gradients for various values of δ are given in Table XIX; values calculated from the equation are also given. The check is quite close. It should be remembered, however, that these are average values and that there is a small varia-

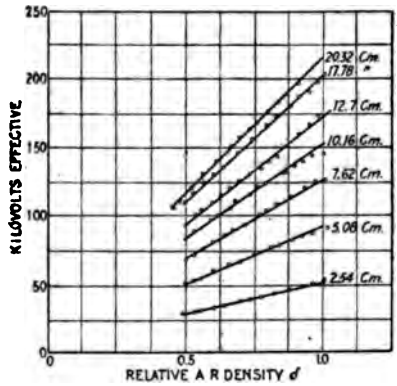

FIG. 6—SPARK-OVER VOLTAGE WITH VARYING AIR DENSITIES
12.5-cm. (4 15/16 in.) spheres. Non-grounded.

Spacing { 2.54 cm. (1 in.)
5.08 cm. (2 in.)
7.62 cm. (3 in.)
10.16 cm. (4 in.)
12.7 cm. (5 in.)
17.78 cm. (7 in.)
20.32 cm. (8 in.) }

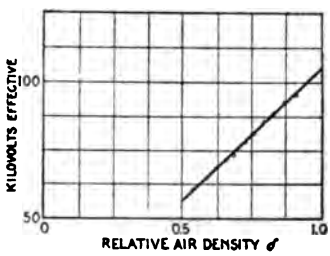

FIG. 7—SPARK-OVER VOLTAGE WITH VARYING AIR DENSITIES
12.5-cm. (4 15/16-in.) spheres grounded.
Spacing 6.35 cm. (2.5 in.).

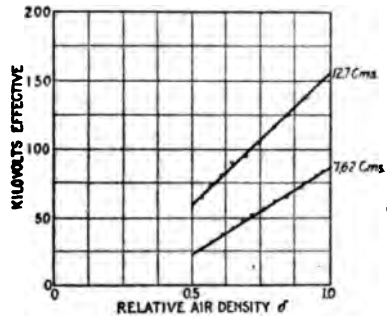

FIG. 8—SPARK-OVER VOLTAGE WITH VARYING AIR DENSITIES
25-cm. (9 7/8-in.) spheres, non-grounded.
Spacing { 12.7 cm. (5 in.).
7.62 cm. (3 in.). }

tion at different spacings over this range, as already explained. (See Figs. 9 and 10).

FREQUENCY

Over the commercial range there is no variation due to frequency. Fig. 11 shows spark-over curves up to 25 kv.

TABLE XIX

AVERAGE EFFECTIVE RUPTURING-GRADIENTS FOR SPHERES OF SEVERAL DIAMETERS AND VARYING AIR DENSITIES.

δ	Diameter of Spheres, cm.							
	2.54		5.08		12.5		25	
	Surface gradients							
	Meas.	Calc.	Meas.	Calc.	Meas.	Calc.	Meas.	Calc.
1.00	28.7	28.5	25.8	25.8	23.6	23.4	22.0	22.2
0.90	26.2	26.1	23.7	23.3	21.8	21.2	19.9	20.1
0.80	24.0	23.7	21.3	21.3	19.6	19.1	17.9	18.0
0.70	21.3	21.2	19.0	19.0	17.4	16.9	15.7	15.9
0.60	18.7	18.7	16.7	16.6	15.2	14.7	13.6	13.8
0.05	16.1	16.1	14.6	14.3	13.0	12.5	11.6	11.7

Columns marked " Calc. " are from $g_s = 19.3\,\delta\left(1 + \frac{0.54}{\sqrt{\delta R}}\right)$

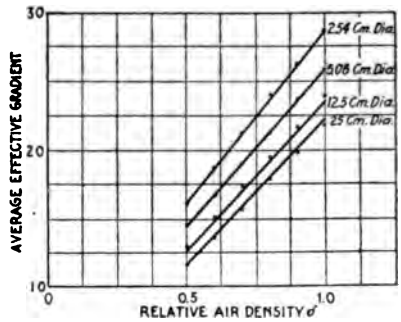

FIG. 9—SURFACE GRADIENT AT VARYING AIR DENSITIES FOR SEVERAL SIZES OF SPHERES

Drawn curves calculated. Points measured values:

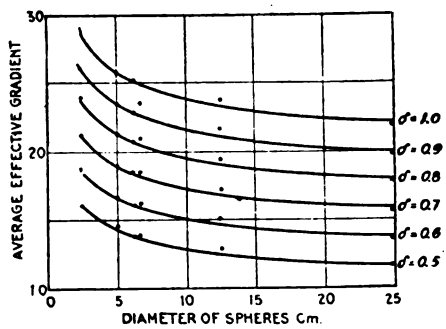

FIG. 10—SURFACE GRADIENT FOR VARYING SIZES OF SPHERES AT SEVERAL AIR DENSITIES.

Drawn lines calculated from formula $g_s = 19.3\delta\left(1 + \frac{0.54}{\sqrt{\delta R}}\right)$

Points measured values.

with 1000-cycle sine-wave current from an alternator. The voltage was measured by a static voltmeter calibrated at 60 cycles. The drawn curve is the 60-cycle curve and the points are measured values. Fig. 12 gives a 60-cycle curve, and also a 40,000-cycle curve from a sine-wave alternator.

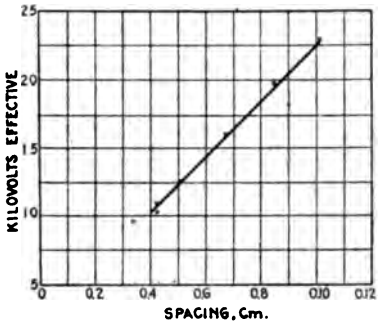

FIG. 11A—SPHERE GAP SPARK-OVER VOLTAGE AT 60 CYCLES AND 1000 CYCLES

5.08-cm. diam. spheres. Drawn curve 60 cycles. Points taken at 1000 cycles.

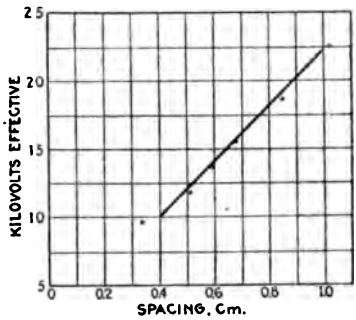

FIG. 11B—SPHERE GAP SPARK-OVER VOLTAGE AT 60 CYCLES AND 1000 CYCLES

12.5-cm. diam. spheres. Drawn curve 60 cycles—points taken at 1000 cycles.

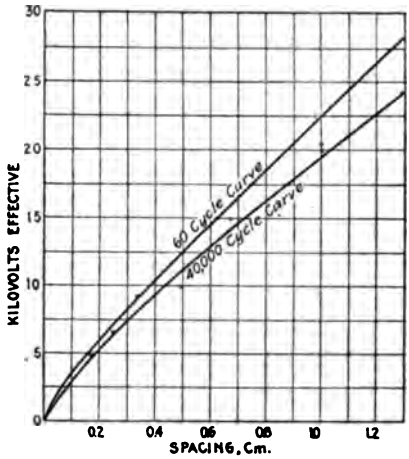

FIG. 12—SPHERE GAP SPARK-OVER VOLTAGE AT 60 CYCLES AND 40,000 CYCLES

Points measured at 40,000 cycles. 5.08-cm. (2-in.) spheres, not polished.

The voltage in this case was measured by a static voltmeter. No special care was taken to polish the sphere surfaces. At low frequencies, at rough places on the electrode surface there is local over-stress, but even if the air is broken down, the loss at these places is very small and the streamers inappreciable.

local voltage rise over parts of the winding. If sufficient resistance is used, these oscillations will be damped out. This is illustrated in Fig. 13, which shows results of a test on a high-voltage transformer on which a 19-cm. gap test is required.

Referring to Fig. 13, the high-voltage winding of the transformer under test is short-circuited and connected to one terminal of the testing transformer. The other terminal of the testing transformer is grounded. The low-voltage winding of the transformer under test is short-circuited, connected to the case and ground. Voltage is gradually applied to the trans-

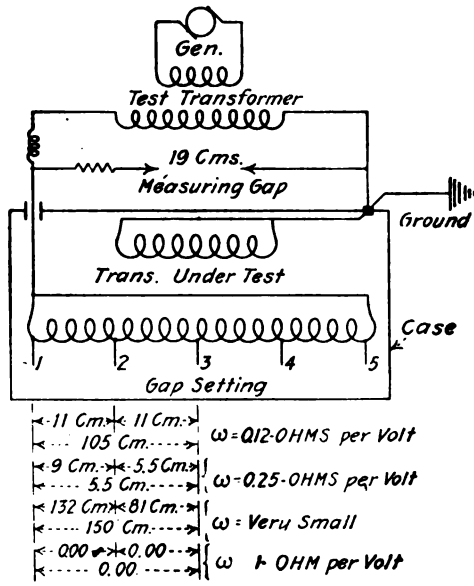

FIG. 13

former under test until the "measuring gap" sparks over. Insulated taps, 1, 2, 3, 4, 5, are brought out at equidistant points from the high-tension winding of the transformer under test. Auxiliary needle gaps are placed between 1 and 2, 2 and 3, and 1 and 3, to measure the voltage which appears across these sections of the winding when the main measuring gap discharges. The numbers on the figure between 1 – 2, 2 – 3 and 1 – 3, represent the sparking distances of the local voltages caused by a discharge of the measuring gap. Four cases are given with different values of resistance ω in the main gap. When

ω equals one ohm per volt the local voltages are completely damped out.

With small resistance in the main gap, a 19-cm. spark-over causes a voltage to build up between coils one and three which sparks over a 150-cm. gap, although the total applied voltage across the transformer is only equivalent to a 19-cm. gap. The apparatus may thus be subjected to strains far beyond reason, and either broken down or very much weakened. Water-tube resistance is the most reliable. A metallic resistance, if non-inductive and of small capacity, may be used. Carbon or graphite rods should be avoided, because, although they may measure up to a very high resistance at low voltage, the resistance may become very low at high voltage by "coherer" action. Where possible the gap should be used only to measure the equivalent transformer ratio and not during test. When the tested apparatus is of such nature that there is considerable incipient arcing before spark-over, it is better to use the spheres to determine the "equivalent ratio" of the transformer below the voltage at which this arcing occurs. It must be remembered that resistances do not dampen out low-frequency surges resulting from a short circuit, etc.

TABLE XX.

POSSIBLE PER CENT ERROR DUE TO PLATES ON 6.25-CM. SPHERE SHANKS.

Spacing cm.	Non-grounded 5 cm. diameter plate 6.25 cm. back of		Grounded 5 cm. diameter plate 6.25 cm. back of		
	both spheres	one sphere	insulated sphere	grounded sphere	both spheres
1.5	0	−0.2	+0.7	−0.7	0
3.0	+1.0	−1.0	+1.5	−1.5	+2.0
6.0	+2.0	−2.0	+3.0	−2.0	+2.0

This table is not meant for making corrections. The arrangement should be such that no corrections are necessary.

APPROXIMATE EFFECT OF DISTANCE ABOVE GROUND WHEN ONE SPHERE IS GROUNDED

Diameters of grounded sphere above ground.	Percentage variations from standard curves for different spacings.		
	$X = 2R$;	$X = R$;	$X = R/2$
0	−10.	5.5	0.0
1	− 4.5	−3.0	0.0
2	− 2.	−1.0	0.0
3	− 1.	−0.5	0.0
4	0.	0.0	0.0
5	+.0.5	+0.3	0.0
6	+ 1.0	+0.5	0.0
10	+ 2.5	+1.0	0.0
20	+ 2.5	+1.0	0.0

Miscellaneous Precautions

In making tests it is desirable to observe the following precautions:

The shanks should not be greater in diameter than 1/5 the sphere diameter. Metal collars, etc., through which shanks extend, should be as small as practicable, and should not come closer to the sphere than the gap length. For the non-grounded case the effect of such objects is a minimum when symmetrical on either side. For the grounded case the effect is considerable. The effect of a large plate or plates on the shanks is given in Table XX. This should show the maximum error in all cases, as the maximum gap setting, and the extreme diameter of collar that is likely to be used in practise, is taken. The sphere diameter should not vary more than 0.1 per cent, and the curvature, measured by a spherometer, should not vary more than 1 per cent from that of a true sphere of the required diameter. The spheres should be twice the gap setting from surroundings.

In Table XX the spacing X is given in terms of radius R, to make the correction applicable to any size of sphere. The distance of the grounded sphere above ground is, for the same reason, given in terms of the sphere diameter. The (+) sign means that a higher voltage is required to arc over the gap than that given by the standard curve. The (−) sign indicates that the spheres read too low. The standard curves were made with the grounded spheres from four to five diameters above ground. In practise it is desirable to work between four and ten diameters; never under three. Above ten the variation in per cent error remains about the same.

When both spheres are insulated, with the transformer neutral at the mid point, there is practically no variation in voltage for different distances above ground.

Great precautions are necessary at very high voltages to prevent leakage over stands, supports, etc., and to prevent corona and brush discharges. Care must also be taken to so place the spheres that external fields are not superposed above the sphere gap. This is likely to result, especially in the non-grounded case, from a large mass of resistance units or connecting leads, etc., in back of and in electrical connection with either sphere. The error may be either plus or minus, as indicated for the small

plates in Table XX. With the water-tube resistance this condition is not likely to obtain, as the tube may be brought directly to the sphere as an extension of the shank.

The author wishes to acknowledge the assistance of Mr. H. K. Humphrey in laboratory work and in making calculations.

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THE ELECTRIC STRENGTH OF AIR—V
The Influence of Frequency

BY J. B. WHITEHEAD AND W. S. GORTON

ABSTRACT OF PAPER

The paper presents the account of an investigation of the influence of frequency on the corona, between 60 and 3000 cycles per second. The wire and coaxial cylinder method was used.

A simple method for measuring the maximum value of an alternating voltage wave has been developed and used for obtaining this maximum value at the critical corona voltage. The gold-leaf electroscope was used to detect the first appearance of corona.

It has been found that for frequencies above 275 cycles per second the corona voltage (maximum value) is not so uniform and constant as it is at frequencies in the neighborhood of 60 cycles.

The indications of the investigation are that at 2000 cycles the corona voltage is lower than it is at 60 cycles by about 3 or 4 per cent.

The experiments reveal several interesting instances of resonance phenomena in the high-tension transformer circuits.

IN AN earlier paper by one of the authors[1] it was shown that within the range 20 to 90 cycles per second the frequency had a measurable effect on the voltage (maximum of the wave) at which the corona begins. The principle of the method of experiment is simple and will be repeated briefly here. The corona is formed about a wire which is stretched coaxially in a metal cylinder, the ends of the cylinder being closed by insulating bushings. Air may be let into the cylinder by a lateral tube near one end and out by a lateral tube near the other end. Immediately after leaving the cylinder the air passes over an insulated electrode which is connected to a gold-leaf electroscope. The walls of the cylinder where the lateral tubes were connected were drilled with numerous small holes. The air could thus pass freely and at the same time the electrode could not be influenced electrostatically by the presence of the highly charged wire at the axis of the cylinder. As the voltage applied to the wire

1. Whitehead, TRANS. A.I.E.E., 1910, Vol. XXIX, Part II, p. 1159; and 1911, Vol. XXX, Part III, p. 1857.

the transformer voltage was effected by varying the field current of the generator.

The corona apparatus proper consisted, as in the earlier experiments, of a wire stretched coaxially in a metal tube. At a point equidistant from the ends of the tube were drilled numerous small holes (about ⅛ in. (3.2 mm.) in diameter). The electrode, which consisted of a brass disk having the same curvature as the tube, was placed over these holes and as near the tube as could conveniently be done without having metallic contact. A grounded metallic shield was placed around the electrode and the connection to the electroscope was made through a hole in the shield, the wire being insulated from the shield by means of a plug of sulfur. The electroscope was a very sensitive one; it gave a workable deflection of the gold-leaf when charged to a potential of 120 volts. In the earlier part of the work the ends of the tube were left open, the wire being stretched between insulating supports situated at some distance from the ends of the tube. Later the ends of the tube were closed by insulating caps, the wire passing through holes in the caps.

The Experiments

Observations were first made on a brass wire 0.089 cm. (0.0350 in.) in diameter in a 4.9-cm. tube. The 500-watt transformer mentioned above was used. The procedure was to raise the primary voltage by increasing the field current of the generator until the electroscope began to discharge. The field current was then decreased until the leak of the electroscope stopped, and then increased again. The voltage at the instant the leak began was read by a hot-wire voltmeter, connected across the low-tension terminals of the transformer. The speed was read by a carefully calibrated tachometer. No attempt was made in these experiments to determine the wave shape, this being a matter of some difficulty at the frequencies in question. In the neighborhood of 600 cycles, the electroscope began to leak at about 80 volts, at 1400 cycles at 73 volts and finally, at 2800 cycles, at 37 volts. The decrease in voltage between 1400 and 2800 cycles was fairly regular.

It seemed highly improbable that the corona voltage actually experienced as great a change as was indicated by the above figures. To test the matter further, a high-tension electrostatic voltmeter was connected across the high-tension terminals of the transformer.

It was found that the corona voltage as indicated by the static voltmeter remained constant. The corona tube was then disconnected from the transformer and at various frequencies the voltage was adjusted so that this voltmeter always read 10 kilovolts. At 60 cycles the low-tension voltage was 82.5 volts, and at 2750 cycles, 31 volts. It was thus seen that the ratio of transformation of this transformer was *over two and one-half times* as great at 2750 cycles as it was at 60 cycles. The cause of this great change is evidently the capacity of the high-tension windings. The charging current taken by the high-tension windings, other things being equal, is directly proportional to the frequency. The reactance of these same windings is also directly proportional to the frequency. Consequently one would expect the disturbing effect of the charging current on the ratio of transformation to be, roughly, directly proportional to the square of the frequency.

That the current taken by the transformer was leading was easily shown. An electrodynamometer connected in the low-tension side indicated 5.5 amperes at 2750 cycles—ten times the value of the current taken at 60 cycles for the same high-tension voltage. The large reactance of this instrument (22 ohms at 2750 cycles) was in this instance of great advantage, because by applying the three-voltmeter method to the dynamometer and transformer the relative power factor of the two could be at once determined. The power factor of the dynamometer alone was determined by series connection with incandescent lamps (assumed non-inductive) and applying the same method. It was found that the current taken by the transformer at 2750 cycles was leading the voltage by about 60 degrees.

For further study of this disturbing influence, tests were made with the 3000-watt transformer described above. The high-tension voltage was not measured, but the effect of different methods of connection of the high-tension coils was studied. All the experiments were conducted at about 2750 cycles. A few examples of the results may prove of interest. With all the high-tension windings in series, one end of the winding connected to ground and the other end open, the transformer took 3.1 amperes at 3.5 volts, the current leading the voltage by about 20 degrees. With the high-tension windings connected two in series, two in parallel, the same point being earthed as formerly, the transformer took 4.0 amperes at 33.5 volts. the current leading the voltage by about 90 degrees. In both cases the low-

tension windings were in series. These two cases are fair samples of the results found in the course of the experiments, and indicate that the method of connecting the high-tension windings has a pronounced influence on the readings of the instruments in the primary side of the transformer.

There was also evidence that at one frequency within the range studied, the transformer was in resonance. With a certain arrangement of the high-tension windings and running at 2750 cycles the switch of the driving motor was opened. With the resulting decrease of speed and frequency, the voltage applied to the transformer and the current taken by it both began to increase and kept on increasing until it was necessary to open the transformer circuit in order not to injure the instruments. There were also indications that the principal factor in these effects was the capacity between winding and core and not between successive portions of the winding. It was found, for example, that the readings on the low-tension side of the transformer depended only upon the maximum voltage (from ground) reached in the high-tension winding. The effect produced by connecting all the coils in series and grounding the middle point of the winding was the same as that produced by connecting the windings two in series and two in parallel and grounding one end.

It appears probable from the results of this paper that the 6 per cent lowering of the corona voltage in going from 20 to 100 cycles reported in the second of this series of papers may be explained as a disturbance due to the capacity in the transformer; all measurements in that work were made on the low-tension side.

Measurement of Maximum Value of Voltage

It was at once evident, from the results of the tests described above, that the measurements of corona voltage would have to be made on the high-tension side of the transformer. This condition, coupled with the unreliability of the oscillograph for the higher frequencies, made it impossible to obtain complete knowledge of the wave shape, except, perhaps, by the use of the cathode ray oscillograph. It is possible, however, to measure both maximum and effective values. Obviously the former is the more important, and probably the determining factor in the formation of corona. The only method available for finding the maximum value is that used by Chubb and Fortescue.[5]

5. Chubb and Fortescue, Trans. A. I. E. E., Vol. XXXII, 1913, p. 739.

among others. The method consists essentially in applying the voltage to be investigated to a condenser and measuring the average value of the current taken by the condenser. Let V represent the maximum value attained by the voltage, C the capacity of the condenser and f the frequency. The time taken by the voltage in passing from its maximum value in one direction, to its maximum in the other, is $\frac{1}{2f}$. In this time the current goes from zero to a maximum and back to zero again. Its average value is equal to the total charge which has passed through the circuit, divided by the time taken for the charge to pass. In symbols:

$$i_{av} = \frac{1}{\frac{1}{2f}} \int_0^{\frac{1}{2f}} i\,dt = \frac{2VC}{\frac{1}{2f}} = 4fVC.$$

$$V = \frac{i_{av}}{4fC} \tag{1}$$

In order to measure the average value of the charging current taken by the condenser, it is necessary to employ a measuring instrument of the permanent magnet type and to rectify the current before it passes into the instrument, or, what amounts to the same thing, to allow only one-half of the current wave to pass through the instrument; in this latter case the reading of the instrument must be multiplied by 2 in order to get the average value of the current. Chubb and Fortescue made use of a mechanical device in order to have only one-half of the current wave pass through the measuring instrument. In the present work the use of a mechanical device was out of the question on account of the high frequencies employed. The mercury arc immediately suggests itself as a non-mechanical rectifier. The rectifying properties of the mercury arc when playing between a mercury and an iron electrode are well known. The arc permits current to flow from the iron electrode to the mercury with only a trifling drop of voltage in the arc; no current can flow in the opposite direction until the applied voltage has risen so high as to cause a vacuum discharge to pass through whatever gas may be present. The mercury arc, moreover, is very rapid in action. It has been shown, for example, that the arc will

be extinguished if the current supply is interrupted for as much as the ten-millionth part of a second. Thus the ionization or conductivity due to the passage of the current dies out with enormous rapidity.

In the present experiments the current taken by the condenser could not itself be used to maintain the arc, first, on account of its small value, and second, because of the necessary method of connection (see Fig. 2). As a consequence the cathode had to be kept active by an arc (maintained by direct current) playing between the cathode and an auxiliary mercury anode. The form of tube which was adopted after considerable experimenting is illustrated in Fig. 1. The tubes were made from German soft glass tubing having approximately an internal diameter of 1 cm. and walls 1 mm. thick. The iron electrode consisted of about 6 cm. of No. 30 iron wire which had been well oxidized by passing through the flame of a blast lamp. The object in making the iron electrode so small was to prevent mercury from condensing on it. In an earlier form of tube the iron electrode was much larger, with the result that mercury condensed on the electrode and dropped off. This last action interfered seriously with the proper functioning of the tube, as, at every fall of a drop, an arc would be started, irrespective of the direction of the voltage acting across the gap. A small wire assumes the temperature of the surrounding mercury vapor much more quickly, consequently condensation is much reduced. The electrode was oxidized in order to prevent the amalgamation of the iron and the condensed mercury. The presence of such an amalgamated surface seems to facilitate condensation enormously. The tubes were exhausted while running until the pressure of the residual gas was less than 0.0001 mm.

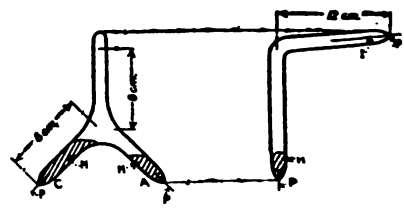

FIG. 1
P, platimum wire; I, iron wire; M, mercury; C, cathode; A, anode.

A diagram of connections is shown in Fig. 2. It will be seen that during one half of the wave the charging current of the condenser passes through one of the two tubes, and during the other half, through the other tube. A direct-current voltmeter was used as a current-measuring instrument. This voltmeter was in circuit with one of the tubes; consequently, in

order to get the average value of the current its reading must be multiplied by 2. The voltmeter gave full scale deflection for a current of approximately 0.01 ampere. The 1.5-volt scale (resistance approximately 156 ohms) of the instrument was used; there was no difference in reading, however, when the 150-volt scale was used instead. The instrument gave the same reading, no matter with which tube it was in circuit; the reading was also unaffected by the presence of a similar instrument in series with the other tube. Each tube, moreover, was carefully tested for the degree of rectification. When the arc was playing between the two mercury electrodes a 240-volt difference of potential was applied between the mercury cathode and the iron electrode, suitable resistances being in the circuit for protection. When the iron electrode was positive with respect to the mercury cathode there was passage of current and the drop of potential across the tube was about 50 volts,

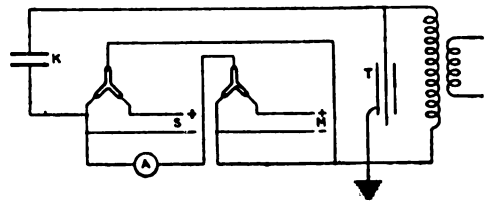

FIG. 2
A, voltmeter; S, special generator; K, condenser; M, city mains; T, corona tube.

independent of the value of current. When the iron electrode was negative with respect to the mercury cathode, the voltmeter showed no deflection and the use of a sensitive galvanometer showed that the current flowing was not greater than the five-millionth part of an ampere. As the tubes were used to rectify currents of the order of magnitude of 0.01 ampere, the rectification was thus practically perfect. Finally, the tubes were set up in series with a condenser, as shown in Fig. 2, and tested at various frequencies from 45 to 75 cycles. The assumption was made that in this range of frequencies the ratio of transformation remained constant and that the wave shape of the high-tension e.m.f. was the same as that of the low-tension e.m.f. The low-tension wave form was taken from oscillograms. The values of the maximum high-tension voltage as measured directly by the mercury tubes, and as calculated from the ratio of transformation and low-tension read-

ings, were the same, within the probable error of the measurements.

Measurement of Effective Value of Voltage

While the knowledge of the maximum value of the voltage so obtained seemed of greatest importance, it was also considered desirable to determine the effective value so as to obtain an approximate indication of the wave form, and ratio of transformation. Concerning minor irregularities on the wave nothing, of course, can be said. An electrostatic voltmeter seemed to be the most suitable instrument. An instrument was needed which would give the effective value of the voltage to ½ of one per cent or better, and which at the same time could be easily damped. These requirements suggested a Crémieu electrostatic-electrodynamic balance. The principle of this instrument is as follows: The voltage to be measured is applied to two disks, one of which is mounted at the end of one arm of a balance beam, the other disk being fixed and in proper relation to the first. The attraction between these disks is balanced by the repulsion exerted between two coils, one of which is fixed at the other end of the balance beam. A constant direct current from some suitable source is passed through these two coils, which are in series. This current is adjusted until the balance is in equilibrium in the same position that it occupies when no electric or magnetic forces are acting. The moment of the electric forces about the knife edge varies directly as the square of the voltage between the disks, and the moment of the magnetic forces varies directly as the square of the current flowing in the coils. Consequently when the balance is brought into the proper position of equilibrium the voltage between the disks is directly proportional to the current flowing in the coils. If, as in the present case, the voltage is alternating, the moment is proportional to the average square of the voltage, which is by definition the square of the effective value. Hence the effective value of the voltage is directly proportional to the current flowing in the coils.

The authors were fortunate in having available a balance beam with a fine agate knife edge, and the usual mounting. All magnetic material had been carefully excluded from the construction of the balance and its glass case. The disks were of aluminum and were 10 cm. in diameter. The distance between the fixed disk and the moving disk was 3.2 cm. The

moving coil consisted of 50 turns of No. 18 copper wire. The fixed coil had 1200 turns of No. 18 wire. The current was led into the moving balance system by means of two silver strips each 0.0013 cm. (0.0005 in.) thick, 1 mm. wide, and 6 cm. long. The points of support of a strip were 4 cm. apart, so that the strip had a very considerable sag. These silver strips would carry about 3.5 amperes before burning out. The largest current they were ever called on to carry was about 1 ampere; with this value of the current the heating of the strips was never enough to cause any disturbance of the balance due to air currents. The strips also had no effect on the sensibility of the balance, nor on the stability of the zero point. In using the balance, current for the coils was taken from a storage battery. When the voltage applied to the disks was steady, readings could be repeated to within $\frac{1}{8}$ of one per cent. When the voltage was unsteady, differences as great as one per cent frequently occurred. The balance was standardized at low frequencies, using the ratio of transformation and low-tension wave form.

Influence of Temperature and Pressure

The influences of pressure and of temperature upon the corona have not been investigated for frequencies above the neighborhood of 60 cycles. While it does not appear probable from the theory of ionization by collision that these influences would suffer any change up to 3000 cycles, it is nevertheless a matter of some uncertainty. Therefore, in order to determine the influence of frequency alone, it was necessary to make observations over the whole range of frequency within a period of time during which the pressure and temperature remained reasonably constant. Three hours was adopted as the length of such a period. This procedure made rather small the number of different frequencies at which it was possible to make observations, but the number of points obtained was sufficient to give a good knowledge of the variation with frequency. In order to shorten the time required for each reading only the maximum of the high-tension voltage wave was read when making observations on the corona. The effective values corresponding to the maximum voltages used were determined after the corona readings, thus greatly facilitating the work, as the effective values of all the different voltages used over the whole range of frequencies were readily determined in a

day. Referring again to Fig. 2, the voltage on the low-tension side of the transformer was read by a Hartmann and Braun hot-wire voltmeter, the series resistance of which was specially wound to avoid change in resistance with frequency. The speed of the generator was read by a carefully calibrated tachometer, accurate within ½ to 1/10 of one per cent, depending on the part of the scale used.

Calibration of Condensers

The condensers used were of the Moscicki type; the dielectric was glass and the condensers were filled with oil to avoid corona at the edges of the metallic coatings. Each condenser had a capacity of about 0.002 microfarad. Now the range of frequency used was from 60 to 3000 cycles, a 50-fold increase. A glance at equation (**1**) will show that if V stays approximately constant over this range (as it actually does) i_{av} will be proportional to the frequency for constant capacity. This state of affairs would mean an enormous variation of the accuracy with the frequency. In order to avoid such a condition the capacity must be varied with the frequency in such a way as to keep the needle of the current-measuring instrument in a suitable part of the scale. This was done by using one condenser at 60 cycles, seven condensers in series for the range from 300 to 600 cycles, and all sixteen condensers in series for the range from 1500 to 3000 cycles. Even with the capacity reduced as much as possible by this means, it was impossible with the larger sizes of wires to go much beyond 1500 cycles, because the rectified current became larger than could be measured by the voltmeter employed; the use of a shunted instrument was, of course, out of the question.

The corona voltage at 60 cycles has been often observed; consequently it was sufficient in the present work to determine how the corona voltage varied with frequency. To this end only the *relative* values of the capacities of the condensers need be known. A special motor-driven generator, excited by a storage battery, furnished alternating current at about 45 cycles. The voltage was measured by an electrodynamometer-type voltmeter. The frequency was measured by a Hartmann and Braun vibrating-reed frequency meter. Condenser No. 1 was put in position in the connections of Fig. 2 and the low-tension voltage, frequency, and rectified current read. From seven to nine observations were made on each condenser. Then,

keeping the frequency, excitation, and all other conditions the same, No. 1 condenser was disconnected and No. 2 connected in its place; then No. 3, and so on for all sixteen condensers. Since the condensers were of approximately the same capacity and the conditions were kept constant, the maximum value of the high-tension voltage was directly proportional to the effective value of the low-tension voltage, and consequently the value of low-tension voltage could be substituted for V in the formula

$$C = \frac{i_{av}}{4fV}$$

in order to find the comparative values of the capacities. The capacity of condenser No. 1 was taken as the unit. The capacity of the condensers when connected in series could be calculated by the usual formula. The needle of the direct-current instrument vibrated with the frequency of the rectified current, the amplitude being about one-half of a division; on this account the accuracy of the reading was only ½ per cent. The frequency could be read to ½ per cent and the alternating voltage to 0.1 per cent. The accuracy of any one reading was consequently about 0.7 per cent. Since from seven to nine readings were taken, the final accuracy attained was about 0.3 per cent. Repeated measurements on one condenser showed that this was actually the order of accuracy attained.

Sizes of Wires and Tubes

Two sizes of corona tubes were used in the course of the experiments, one having a diameter of 4.58 cm. and the other a diameter of 6.35 cm. The diameters of the wires used were as follows: 0.317 cm. (0.1249 in.), 0.234 cm. (0.0924 in.), 0.194 cm. (0.0763 in.), 0.164 cm. (0.0644 in.), 0.106 cm. (0.0418 in.), 0.089 cm. (0.0350 in.). All of these sizes were of brass, except the wire 0.194 cm. in diameter, which was of tool steel. The smaller sizes were made straight by heating with an electric current while under tension. The larger sizes were rods which needed no such treatment. Each time before being used the wire was polished with the very finest emery paper until the latter became glazed with brass. A final polish was given with tissue paper. This treatment produced a very good polish. In the earlier part of the work the tube was left open at the ends; for the most part, however, the ends were closed with insula-

ting caps. No difference between the two cases could be detected.

Accuracy of Observations

The rectified current could be read to 0.1 per cent at frequencies of 300 and more, the needle standing without vibration. The speed could be read always to ½ per cent and generally still more closely. The capacity of the condensers had been determined to 0.3 per cent. Consequently any one observation of the maximum voltage at 300 cycles and over was accurate to 0.6 per cent. At 60 cycles the rectified current could be read to ½ per cent, the frequency (the generator was not readily accessible) to ½ per cent, and the capacity, as before, was determined to 0.3 per cent. The accuracy was consequently at 0.8 per cent. For convenience, the current required to deflect the direct-current voltmeter one scale division, and the capacity of condenser No. 1, were chosen as units of observation. The formula for the maximum voltage then becomes

$$V = k \frac{E}{fC} \tag{2}$$

k being a constant of the apparatus and E the reading of the voltmeter. It was assumed, on the basis of information from the Bureau of Standards, that the capacity of the Moscicki condenser varies only a fraction of one per cent over the range of frequency investigated.

The Observations

It was possible in the three-hour period mentioned above, to make one or sometimes two sets of observations at 60 cycles, two sets in the neighborhood of 600 cycles and several sets between 1500 cycles and the maximum frequency obtainable, as limited by the rated speed of the machine or more often by the capacity of the direct-current instrument. Each set of readings consisted of from five to twelve observations of the corona voltage. As a general thing, repeated sets of observations agreed very closely, that is, within a few tenths of one per cent, but sometimes they would differ by as much as 2 per cent. These differences could not be accounted for. The constancy of the corona voltage was not always such that full advantage could be taken of the accuracy of the method, and apparent constancy of conditions. The following table is an

example of a set of readings in which the agreement was very good:

D-C. Instrument	Low-tens. voltage of trans.	Speed in rev. per min.
140.2	102.3	968
140.5	102.3	968
140.0	102.0	973
140.0	102.7	968
140.0	102.1	968
140.0	102.1	
139.5	102.1	969
139.3	101.5	
139.8	102.1	968

The following table is an example of a rather bad set:

D-C. Instrument	Low-tens. voltage of trans.	Speed in rev. per min.
89.0		1050
91.0	Off scale	1038
90.8		1038
91.0	*i. e.*, over 130 volts.	1038
90.3		1038
90.9		1038
91.9		1037

The results for the tube 4.58 cm. in diameter are given in Table I, and those for the 6.35-cm. tube are given in Table II. The voltages given were calculated by means of formula (**2**). These results are plotted in Figs. 3 and 4 respectively. In these figures the points of each set are connected by straight lines in order to make interpretation easier. Each point represents a series of from five to twelve observations.

Table III gives the values of effective high-tension voltages, ratio of transformation, and peak factor, that is, ratio of maximum to effective high-tension voltage, for various voltages and frequencies over the entire range explored. The maximum values are those observed with the condenser and mercury-arc rectifier apparatus as described. The peak factor at 60 cycles was about 1.48. The range of peak factors obtained in the course of the observations consequently is from 1.66 to 1.27. The wave of voltage, therefore, did not depart greatly from

TABLE I

CORONA VOLTAGES FOR WIRES IN TUBE 4.58 CM. IN DIAMETER.

Diam. of wire	Series of observations	Frequency in cycles per second	Voltage / k
0.317 cm. (0.1249 in.)		59.0	1.242
		1338	1.191
		1680	1.202
0.234 cm. (0.0924 in.)	1	59.2	1.079
		558	1.061
		575	1.063
		1368	1.048
		1372	1.060
		1914	1.042
		1948	1.043
	2	58.5	1.081
		583	1.039
		1362	1.037
		1370	1.053
		1826	1.037
		1968	1.047
	3	58.0	1.076
		585	1.040
		1368	1.038
		1672	1.043
		1970	1.041
		2076	1.042
0.194 cm. (0.0763 in.) (tool steel)	1	59.5	0.998
		569	1.960
		2006	0.976
	2	58.8	0.999
		566	0.977
		567	0.973
		1336	0.986
		1884	0.982
	3	60.5	0.995
		590	0.950
		590	0.951
		1370	0.968
		1410	0.963
		1692	0.967
		2058	0.967
		2122	0.958

Diam. of wire	Series of observations	Frequency in cycles per second	Voltage / k
0.164 cm. (0.0644 in.)	1	59.6	0.904
		568	0.877
		576	0.893
		1376	0.895
		1418	0.888
		1754	0.885
		2176	0.884
		2412	0.880
	2	58.9	0.919
		587	0.882
		1378	0.886
		1396	0.886
		1730	0.878
		2110	0.880
		2372	0.875
	3	58.3	0.928
		584	0.880
		1368	0.885
		1674	0.894
		2054	0.890
0.106 cm. (0.0418 in.)	1	59.5	0.758
		573	0.738
		575	0.738
		2640	0.737
		2650	0.739
		2822	0.728
	2	59.1	0.748
		598	0.728
		598	0.729
		1416	0.716
		2134	0.725
		2908	0.700
		2966	0.700
0.089 cm. (0.0350 in.)	1	59.5	0.689
		60.0	0.683
		558	0.686
		570	0.680
		2822	0.666
	2	59.4	0.683
		573	0.683
		1406	0.680
		2792	0.677

sine shape. The ratio of transformation of the transformer :eased between 60 cycles and 2958 cycles by about 30 per .t.

TABLE II

CORONA VOLTAGES FOR WIRES IN TUBE 6.35 CM. IN DIAMETER.

ım. of wire	Series of observations	Frequency in cycles per second	Voltage / k	Diam. of wire	Series of observations	Frequency in cycles per second	Voltage / k
	1	59.8	1.370		1	58.6	0.994
		578	1.313			585	0.955
		1294	1.338			1372	0.961
		1622	1.313			1740	0.952
317 cm.						2102	0.959
249 in.)	2	59.4	1.362		2a (without series inductance in low-tension circuit.)	272	1.031
		274	1.402			274	1.037
		346	1.373			347	1.031
		423	1.361	0.164 cm. (0.0644 in.)		473	0.982
		502	1.366			528	1.016
		566	1.360			584	1.004
		1298	1.350				
		1440	1.350				
		1638	1.336				
	1	58.3	1.198		2b (with series inductance in low-tension circuit.)	275	1.039
		585	1.147			346	1.019
		1360	1.148			388	0.996
		1684	1.161			423	0.982
	2	58.9	1.186			463	1.010
		284	1.223			528	1.011
		316	1.212			570	1.019
		354	1.191				
		467	1.091				
		529	1.166	0.106 cm. (0.0418 in.)	1	58.7	0.796
234 cm.		566	1.191			59.4	0.795
924 in.)		570	1.181			594	0.765
		1098	1.166			1388	0.776
		1460	1.170			1766	0.770
		1848	1.151			2134	0.775
						2644	0.761
	3	58.1	1.175				
		58.6	1.191				
		274	1.191				
		342	1.197				
		421	1.164				
		469	1.122				
		527	1.159				
		570	1.174				
		1392	1.174				

DISCUSSION

:eferring to Figs. 3 and 4, it will be noticed that there is a siderable amount of irregularity in the locations of the cessive points with reference to smooth curves. This

TABLE 1

CORONA VOLTAGES FOR WIRES IN TUBE 4.58 CM. IN DIAMETER.

Diam. of wire	Series of observations	Frequency in cycles per second	Voltage / k
0.317 cm. (0.1249 in.)		59.0	1.242
		1338	1.191
		1680	1.202
0.234 cm. (0.0924 in.)	1	59.2	1.079
		558	1.061
		575	1.063
		1368	1.048
		1372	1.060
		1914	1.042
		1948	1.043
	2	58.5	1.081
		583	1.039
		1362	1.037
		1370	1.053
		1826	1.037
		1968	1.047
	3	58.0	1.076
		585	1.040
		1368	1.038
		1672	1.043
		1970	1.041
		2076	1.042
0.194 cm. (0.0763 in.) (tool steel)	1	59.5	0.998
		569	1.960
		2006	0.976
	2	58.8	0.999
		566	0.977
		567	0.973
		1336	0.986
		1884	0.982
	3	60.5	0.995
		590	0.950
		590	0.951
		1370	0.968
		1410	0.963
		1692	0.967
		2058	0.967
		2122	0.958

Diam. of wire	Series of observations	Frequency in cycles per second	Voltage / k
0.164 cm. (0.0644 in.)	1	59.6	0.904
		568	0.877
		576	0.893
		1376	0.895
		1418	0.888
		1754	0.885
		2176	0.884
		2412	0.880
	2	58.9	0.919
		587	0.882
		1378	0.886
		1396	0.886
		1730	0.878
		2110	0.880
		2372	0.875
	3	58.3	0.928
		584	0.880
		1368	0.885
		1674	0.894
		2054	0.890
0.106 cm. (0.0418 in.)	1	59.5	0.758
		573	0.738
		575	0.738
		2640	0.737
		2650	0.739
		2822	0.728
	2	59.1	0.748
		598	0.728
		598	0.729
		1416	0.716
		2134	0.725
		2908	0.700
		2966	0.700
0.089 cm. (0.0350 in.)	1	59.5	0.689
		60.0	0.683
		558	0.686
		570	0.680
		2822	0.666
	2	59.4	0.683
		573	0.683
		1406	0.680
		2792	0.677

the sine shape. The ratio of transformation of the transformer increased between 60 cycles and 2958 cycles by about 30 per cent.

TABLE II

CORONA VOLTAGES FOR WIRES IN TUBE 6.35 CM. IN DIAMETER.

Diam. of wire	Series of observations	Frequency in cycles per second	Voltage / k
0.317 cm. (0.1249 in.)	1	59.8	1.370
		578	1.313
		1294	1.338
		1622	1.313
	2	59.4	1.362
		274	1.402
		346	1.373
		423	1.361
		502	1.366
		566	1.360
		1298	1.350
		1440	1.350
		1638	1.336
0.234 cm. (0.0924 in.)	1	58.3	1.198
		585	1.147
		1360	1.148
		1684	1.161
	2	58.9	1.186
		284	1.223
		316	1.212
		354	1.191
		467	1.091
		529	1.166
		566	1.191
		570	1.181
		1098	1.166
		1460	1.170
		1848	1.151
	3	58.1	1.175
		58.6	1.191
		274	1.191
		342	1.197
		421	1.164
		469	1.122
		527	1.159
		570	1.174
		1392	1.174
0.164 cm. (0.0644 in.)	1	58.6	0.994
		585	0.955
		1372	0.961
		1740	0.952
		2102	0.959
	2a (without series inductance in low-tension circuit.)	272	1.031
		274	1.037
		347	1.031
		473	0.982
		528	1.016
		584	1.004
	2b (with series inductance in low-tension circuit.)	275	1.039
		346	1.019
		388	0.996
		423	0.982
		463	1.010
		528	1.011
		570	1.019
0.106 cm. (0.0418 in.)	1	58.7	0.796
		59.4	0.795
		594	0.765
		1388	0.776
		1766	0.770
		2134	0.775
		2644	0.761

DISCUSSION

Referring to Figs. 3 and 4, it will be noticed that there is a considerable amount of irregularity in the locations of the successive points with reference to smooth curves. This

It will be noticed that the points showing most serious departure from a regular curve are those for frequencies within the range 300 to 600 cycles. The observations in this range have caused much trouble, and for this reason the curves have been drawn in dotted lines, indicating uncertainty as to the observations. As nearly as could be determined, there was a tendency for the maximum corona voltage to take a sharp dip in passing through this range. There were, however, several accompanying conditions of experiment which may well account for the irregular results. For example, the connection of the high-tension winding of the transformer had to be altered in this range in order to make the necessary change in the corona voltage. Attention has already been drawn to the influence of this change on the charging current of the windings. It will be seen from Table III that there is evidence of a difference in the high-tension wave form for the series connection and the parallel connection of the two halves of the high-tension winding. Further, at about 425 cycles, and within a certain range of field excitation of the generator, there was a pronounced evidence of resonance in the high-tension circuit. On the smallest possible change in the field current of the generator, the reading of the d-c. instrument, indicating the maximum voltage, increased sharply from 35 to 80. Observations taken at this frequency on a larger wire and for values of voltage above the unstable region, showed no unusual conditions other than a slight irregularity of voltage which was readily damped out by series inductance in the low-tension circuit.

Still further evidence of abnormal conditions in the range from 300 to 600 cycles was found in the different results obtained in the series and parallel connections of the high-tension winding. Between 270 and 425 cycles, with the series connection, a spark would pass between wire and outer tube at a voltage only about ½ that required to produce corona when the high-tension winding was connected in parallel. The same phenomenon was observed in the range 450 to 600 cycles, with the exception that the parallel connection gave the spark at low voltage. This spark was intermittent, apparently localized, and very different from the usual uniform corona. The impression made was that there was a series of short impulses of abnormally high voltage.

While it is evident, therefore, that there were a number of abnormal conditions surrounding the observations in the region 300 to 600 cycles, there is no obvious reason why, if the conditions

were steady, the maximum value of voltage could not have been picked out by the mercury arc peak voltmeter. There is every indication that the mercury arc is instantaneous in action. Nevertheless, there seems to be no other conclusion than that the conditions of resonance described above, introduced very brief voltage impulses of high value which the mercury arc and condensers did not pick out. Considerable variation was obtained in the wave form by connecting the armatures of the two generators in series, thus obtaining a pronounced fifth harmonic. There was no resulting variation of the corona voltage; such variation, however, could hardly be expected unless the frequencies were far higher than 3000 cycles.

The corona from 1500 cycles upward appears also to differ qualitatively from that at lower frequencies. It is a common observation at 60 cycles that the gold-leaf of the electroscope descends in a jerky fashion when corona voltage is reached. The time taken for complete discharge is about 30 seconds. This has been attributed to the exact constancy of the corona voltage and the usual slight variation of the impressed voltage. From 300 to 600 cycles the electroscope discharged quickly but steadily, the time for discharge being one or two seconds. From 1500 to 3000 cycles the electroscope discharged in a very small fraction of a second, the gold-leaf descending practically instantaneously. There is absolutely no indication of leak before any of these observations.

A further interesting phenomenon at the higher frequencies was the vibration of the wire in the case of the open tube, when the points of suspension were some distance beyond the ends. At 1500 cycles the presence of corona caused the wire to vibrate greatly. There was no vibration before the appearance of the corona. The tension on the wire was altered through a wide range, but the vibration persisted unchanged. There is apparently, therefore, no connection between the frequency of the voltage and the natural period of vibration of the stretched wire. At 60 cycles the wire remained perfectly steady, even when surrounded by a strong corona. These vibrations, therefore, are apparently forced vibrations due to some property of the corona.

In considering the possible influence of the frequency on the appearance of corona in terms of the theory of secondary ionization or ionization by collision, there are three possible ways in which this influence might act: (1) The conditions of stable equilibrium

of the systems of vibrating electrons within the atom of the gas would be affected in different degrees by periodic electric forces of different frequencies. (2) With increasing frequencies, the time during which a single free moving electron is acted on by the electric force in one direction would be less; consequently the velocity acquired and energy available for ionization by collision would be less. (3) It has been suggested that the corona occurs when the density of ionization in the gas at the surface of the wire reaches a certain value. This increase in density results from the passage inward of electrons from a distance. As they move in they create more ions by collision. More ions are created on the inward path than are lost by recombination during the reverse half of the alternating cycle. At higher frequencies the rate at which the ions would reach the wire would probably be lowered, thus demanding a higher voltage for the appearance of corona.

Of these three possible methods of explanation the first two are apparently untenable, certainly for the range of frequencies investigated in these experiments, by reason of the fact that the periods of vibration within the atom and the time during which an electron passes from one collision to another, are infinitesimally small, compared with the time of reversal of the electric force at the frequencies investigated.

The experiments were carried out in the Physical Laboratory of the Johns Hopkins University. The authors wish to acknowledge the valuable assistance of Professor A. H. Pfund, in connection with the mercury lamps, and of Mr. M. W. Pullen at various times throughout the work.

Summary

The most important results of the work are as follows:

(1) The corona voltage at 2000 cycles is lower by 3 or 4 per cent than it is at 60 cycles.

(2) The corona in the range 300 to 3000 cycles has a number of qualitative differences from that at 60 cycles.

(3) Convenient methods for measuring high-tension maximum and effective voltages at frequencies up to 3000 cycles have been devised.

(4) An instance of resonance due to the capacity of the high-tension windings of a transformer is recorded.

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SPHERE GAP DISCHARGE VOLTAGES AT HIGH FREQUENCIES

BY J. CAMERON CLARK AND HARRIS J. RYAN

ABSTRACT OF PAPER

The paper describes a series of experiments made by the authors to determine the values of steady high-frequency, high-voltage currents required to discharge between seven-inch copper spheres in air, at ordinary temperatures and barometric pressures. A 15-kw. arc generator was used as the source of high-frequency sustained high voltage, and the apparatus employed in securing and measuring currents of 123,000, 255,000 and 612,500 cycles is described in detail.

The sphere-gap standard consisted of electrolytic copper spheres mounted on the ends of brass tubes in treated wooden frames, and the gap lengths were accurately determined by means of calipers and micrometer screw or steel scale.

The results obtained are given in Tables II and III and are also charted in curves I and II, Fig. 5. The 123,000-cycle values show a right-line relation between sphere gaps and discharge voltage, which line, when extended, passes through the origin. The high-frequency voltages are almost uniformly 4.5 kv. below the 25-cycle voltages observed by Chubb and Fortescue.

INTRODUCTION

THE predatory character of high-frequency currents due to accidental causes on transmission lines is now generally recognized, especially with reference to insulation. The modern high-power radiotelegraph has encountered occasional difficulty in the maintenance of insulation that is also stressed with high-frequency high voltage. These facts have emphasized the need of more quantitative knowledge of high-frequency phenomena. To obtain this knowledge many laboratory studies and measurements will have to be made to provide more conclusive data and trained mental equipments required to interpret causes of insulation failure and to eliminate them.

To aid in these matters we have undertaken to determine the values of steady high-frequency high voltages required to discharge between seven-inch (17.7-cm.) copper spheres, in air, at ordinary temperatures and barometric pressures.

High-Frequency Sustained High-Voltage Source

A 15-kw. Poulsen-Federal arc generator was used. See Fig. 1. The arc is drawn in a powerful magnetic field and surrounded by water-cooled illuminating gas. A slowly-rotating carbon rod forms the cathode, and a water-cooled bronze lug forms the anode. The characteristics of this particular arc have not as yet been fully determined. At 17.6 amperes direct current through the arc and 12.5 amperes alternating current at 123,000 cycles per second in the oscillating circuit, the arc is stable at 1200 continuous volts. Under these conditions the resistance ballast at R is all cut out, and the power

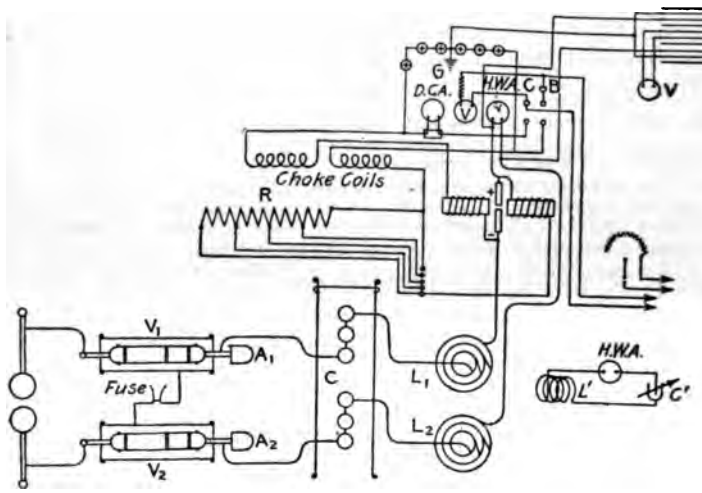

Fig. 1

consumed in the oscillating circuit is chiefly that lost in the carborundum safety resistance rods, SR, in series with the sphere gap. This power amounts to about one kw. There are two of these rods, each $8\frac{3}{4}$ in. (222.25 mm.) long and $\frac{3}{4}$ in. (19.05 mm.) in diameter. The charging current taken by the seven-inch (17.7-cm.) spheres at 123,000 cycles is sufficient to maintain the rods at a bright cherry-red temperature.

The insulation of the field coils of the arc generator must be extra heavy, as the duty put upon it is severe. The outer terminals of the coils are connected to the anode and cathode of the arc. Correspondingly, the inner terminals are connected to the inductances that protect the direct-current generator

from "static". Adjustable static arrester gaps shunt these field coils to short-circuit the "kick" of the field when the arc breaks. The arc will break occasionally, stopping the current through the field coils with suddenness. The discharge from these field coils will puncture their own insulation and that of the direct-current generators if such inductances and dischargers are not used. For greater safety in this regard, a series of carbon-filament incandescent lamps connects across the terminals of the generator. The middle of the series is grounded. Two 7.5-kw., 600-volt direct-current generators furnish current to the arc-generator. They are connected in series, with their mid-connection grounded. The first machine is separately excited from a 125-volt source. The 600-volt field of the second generator is excited with current taken from the armature of the first generator. Thus a rheostat in the field of the first generator controls the total direct-current supply voltage. This rheostat is mounted so that one can conveniently use it to adjust the direct-current supply voltage when he is starting the arc generator or adjusting its action.

The arc generator equipment includes one 50-ampere, direct-current ammeter showing the average direct current drawn from the continuous-current supply generators; one 30-ampere Hartmann and Braun "hot-band" ammeter measuring the high-frequency amperes circulating in the oscillating circuit; one voltmeter for reading the continuous-current supply voltage; and a high-frequency voltage gage connected across the arc to enable one to know the voltage duty demanded of the arc to set up a given current in the oscillating circuit. The last instrument is easily made by connecting a one-ampere hot-wire ammeter in series with two pairs of common tin sheets at ½ in. (12.7 mm.) separation, functioning as a condenser, and connected across the arc. The charging current taken by such a condenser, as indicated by the hot-wire ammeter, is roughly proportional to the high-frequency voltage duty demanded of the arc. Such voltage is decidedly of irregular wave form, so that this instrument functions simply as a *voltage gage*.

The inductance in the oscillating circuit is made up of approximately 2000 ft. (609.6 m.) of ¼-in. (6.3-mm.) soft copper tubing, forming six helices of 25 turns each. Each helix is mounted on six hard-rubber rods. The helices have graded diameters so that they may be telescoped to form one six-helix inductance or a pair of inductances of three helices each. The

travel of the turns is the same for all helices,—an important matter when these large inductances are to be formed by telescoping. When the travels are not the same, *i.e.*, when they reverse from layer to layer as in the ordinary solenoid, the distributed capacity of the inductance is broken into chunks, causing turbulent interference with the growth of the oscillating current. In a nest of helices the circuit leads through the first from the bottom turn to the top turn, thence downward to the bottom turn of the next helix, then out at the top, and again in at the bottom of the next, and so on through the whole set. Oscillating currents are easily driven through inductances of this sort when connected in series with suitable condensers. Even with this favorable construction the helices may not be nested in a single set because the duty demanded of the arc will easily exceed its voltage capacity before a fair value of high-frequency current has been set up. It is necessary to mount the helices in two sets, preferably of equal inductances. Then, when a single condenser is connected symmetrically between the two inductances, and in series therewith, the phase displacements that the oscillating currents encounter with respect to the arc are opposed and balanced. The high-frequency voltage duty demanded of the arc is correspondingly light. Without resorting to delicate balancing, 50,000 volts and 12.5 amperes at a frequency of 123,000 cycles per second may be developed in this apparatus. With greater care in balancing than we have so far employed, higher oscillating voltages can doubtless be developed.

The main condenser in the oscillating circuit is made up as shown at *C* in the diagram of the complete outfit given in Fig. 1. Each electrode is formed of cylinders of galvanized sheet iron seven ft. (2.1 m.) long and five in. (127 mm.) in diameter, equipped with hemispherical ends. They are also equipped with hooks and eyes so that chains of parallel cylinders may thus be formed. The capacity can be increased or decreased by attaching and detaching one or more of these cylinders from each of the two electrode chains. This feature enables the capacity in the oscillating circuit, and therefore the frequency, to be varied over wide limits. At present this main condenser is equipped with a chain of four cylinders at each electrode. The chains hang in a vertical plane between a pair of neutral plates forming a hood about the capacity cylinders, as shown in Fig. 1. The frames of these plates are made of common

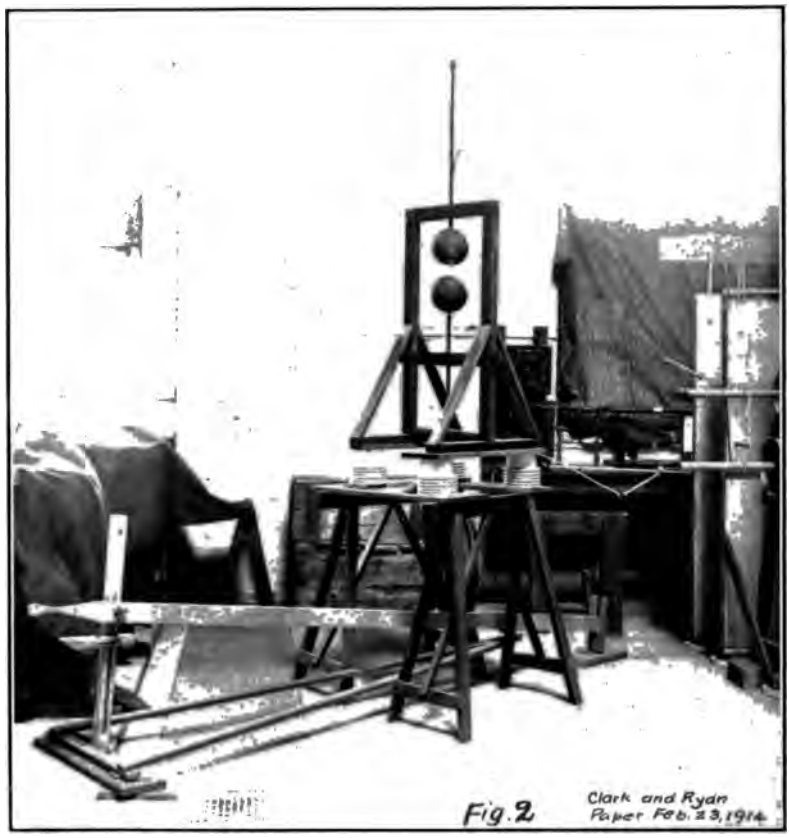

FIG. 2

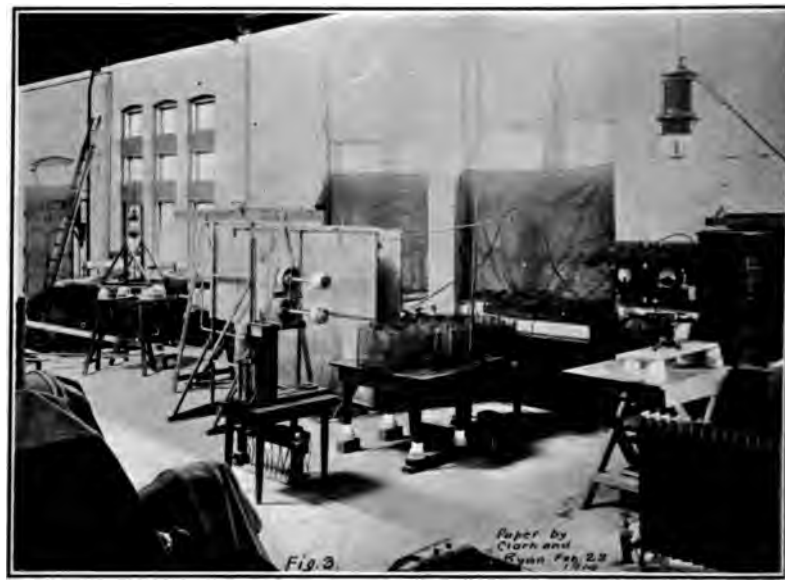

FIG. 3

FIG. 4

galvanized iron pipe, $\frac{3}{4}$ in. (19.05 mm.) internal diameter; the bodies of the plates are constructed of galvanized iron, 23-mil sheets. The plates are tied together with a conductor. They are insulated from ground for a small portion of the total oscillating voltage, for unless special care is taken there is some unbalancing that sets up a potential between the plates and ground. The illustrations, Figs. 2, 3 and 4, give an idea of the actual manner in which the above parts of the generating equipment are formed and arranged. To the capacity of the main condenser there is necessarily added the capacity of the concentric-cylinder voltmeter condenser, V_1 V_2, to be considered later.

In the final stage of the present undertaking, the number of helices was doubled by placing the six copper tubular helices in one nest and by the addition of a set of six helices of the same size, in which the conductor used is a "flat magnet wire" 0.34 by 0.04 in. (8.6 by 1 mm.) in section. The latter set was made up, primarily, to serve as a protective inductance at the main terminal of a low-frequency high-voltage series of transformers, the other main terminal being grounded. However, by giving the helices of this set proper dimensions they could be used along with the regular set for the generation and measurement of higher voltages at lower frequencies in the standardization of the sphere-gap voltmeter. When using the largest capacity and self-induction that the equipment thus provides, 12.5 amperes at 100,000 volts and 85,000 cycles per second are produced in the oscillating circuit. Correspondingly, when the capacity is reduced to the lowest practicable limit, viz., that of the voltmeter condenser, and the self-induction is limited to that of the pair of small innermost helices, 8.1 amperes and 13,000 volts at 612,500 cycles are produced.

The carborundum protective resistance in series with the sphere-gap voltmeter could not be used at frequencies much above 123,000 cycles. This is due to the magnitude of the charging currents inevitably taken by the spheres and their connections, which cause excessive losses in resistances proportioned so as to limit properly the 1200-volt direct power-current that follows a discharge across the gap. At higher frequencies a fine-wire fuse, guarded to prevent corona, was used to limit the injury produced by the power currents. The capacity of the fuse must necessarily be large enough to carry the charging currents taken by the spheres and their connections. On

this account such fuse capacity cannot be made small enough entirely to prevent injury to the spheres. To overcome this difficulty in the later stages of the work, when frequencies higher than 123,000 cycles were used, the Fortescue-Chubb-Farnsworth mounting for the spheres had to be slightly modified. The brass rods supporting the seven-in. (17.7-cm.) spheres were terminated in shallow cups with inside surfaces fitting them. The spheres were then mounted upon these cups, being held in place by thin sheet brass halters and rubber bands. These changes in the sphere gap standard do not appear to be of material consequence as affecting its integrity for the present class of measurements, while they permit the spheres to be rotated when their adjacent surfaces have been injured so as to bring into use new and uninjured surfaces. By this means the reliable useful life of the spheres is prolonged to such an extent that their renewal cost becomes nominal.

High-Frequency Meter

In the present undertaking a reliable frequency or wave meter is of prime importance. The frequency meter employed was made by connecting an inductance standard in series with a variable condenser of reliable make and of a type commonly employed in radio work. Three entirely independent methods were employed for standardizing this meter.

I. *By Calculation*: In this method the value of the inductance was calculated. The conductor used in its construction was enamel-insulated litzen draht, silk-jacketed. When constructed, the dimensions were obtained with some care. Perry's formula[1] and Doggett's method[2] were used to calculate independent values of the inductance. The results obtained were 879.0 and 882.5 microhenrys. The variable condenser was compared with a standardized condenser of the Federal Telegraph Company. It was also compared with an air-core standard formed of two concentric brass tubes. The scale of the condenser was found to be true and linear. Its total capacity at the 180-deg. setting compared with the Federal standard was found to be 0.00405 microfarad and with the brass tube standard 0.00407 microfarad.

1. Perry's Approximate Self-Inductance Formula. *Bulletin*, Bureau of Standards. Vol. 8, No. 1, p. 136. Jan. 1, 1912.

2. Leonard A. Doggett. The Inductance of Air-Cored Solenoids. *Electrical World*, Vol. 63, p. 259, January 31, 1914.

II. *By Direct Measurement, as follows*: At a definite setting of the wave meter the current through and the voltage across the terminals of the meter condenser were read. A one-ampere Hartmann and Braun hot-band ammeter was used for the current and a Kelvin multicellular electrostatic voltmeter for the voltage. The latter instrument is essentially an air-core condenser. Its capacity could be determined conveniently and accurately by noting the change in the frequency meter reading that was caused by its presence. An exact correction on its account could therefore be made. The frequency was then calculated from the simple and well-known relation of voltage, current and capacity. This value was found to be 123,000 cycles to check with 122,500 cycles obtained by method I.

III. The wave meter was then taken to the factory of the Federal Telegraph Company in Palo Alto. There, through the courtesy of Mr. Ralph Beal, it was compared with the wave meter that had been standardized by the Bureau of Standards. The two wave meters were found to be in close agreement, differing only by $\frac{1}{4}$ per cent.

For higher frequencies the wave meter was recalibrated by method II to eliminate errors that appear due to the internal capacity of the wave meter inductance.

High-Frequency High-Voltage Meters

The high voltages generated in the main condenser, C, Fig. 1, of the oscillating circuit, contain pure sine waves of a single frequency only. The rough pulsating voltages of the generator arc are completely absorbed by the main inductances, $L_1 L_2$, in the oscillating circuit. A reliable voltage meter was, therefore, made out of a suitable condenser of known capacity connected in series with a hot-band ammeter that is free of frequency effects.

For balancing purposes and to employ convenient dimensions in other respects, it was found best in the present work to make up and use two of these condenser-type voltage meters. The manner of their construction is shown at $V_1 V_2$ in Fig. 1. They were made in principle the same as that used by Chubb and Fortescue in standardizing the Farnsworth-Fortescue sphere gap voltmeter.[3] Each condenser was made concentric and near to these specified dimensions: Outer cylinder: inner diameter 11.0 in. (27.9 cm.) length 72 in. (1.8 m.). Inner cylinder: outer diameter 7.0 in. (17.7 cm.), gross length, not including wood-

3. L. W. Chubb and C. Fortescue, Trans. A.I.E.E., Vol. XXXII, 1913, p. 739.

them for regularity of surface curvature from the commercial float ball product. Well-impregnated paraffined oak was used for the cross pieces through which the brass tubes pass to support the spheres. The rest of the frame was made of Oregon pine. Under the stress of high-frequency high voltage all dielectrics accept large charging currents. Ample and close electrode contact, entirely free of all corona, must be made, to lead these charging currents into the stressed dielectric so as to prevent burning or other injury. Accordingly the holes through the oak cross pieces were bushed with brass sleeves cemented to the wood by paraffin treatment. Without this precaution the frame will promptly be set afire. For balancing purposes we had to set this sphere gap standard rather high off the floor. For reasons given above, it could not be operated with one terminal grounded as recommended by Fortescue, Chubb and Farnsworth. We also used a long wooden lever and screw jack to facilitate accurate gap settings. Gap lengths were determined by means of calipers and micrometer screw or steel scale.

Finally, reference is made to the three illustrations Figs. 2, 3 and 4, which give to the eye much additional information relating to the construction and arrangement of the equipment as employed and above described.

Features of Unsteadiness in the High-Frequency High Voltages Generated in the Apparatus as Used and Described Above

The character of the high-frequency voltages was examined with the aid of the cathode ray cyclograph. The ray was given an alternating deflection in one plane magnetically, and in a quadrature plane, electrostatically. The magnet deflections were produced by the oscillating currents. Limitations in the behavior of the cathode ray tube made it necessary to use an air-core transformer in series with the oscillating circuit. The secondary of this transformer was short-circuited through the current coils of the cyclograph and grounded. Thus the cathode ray was not subjected to the potential disturbances that occur when the deflecting coils are directly connected in series with the oscillating circuit adjacent to an ungrounded electrode of the generator-arc.

The ray was deflected electrostatically by "quadrants" charged with the potentials of spherical electrodes that were

dipped into the powerful electrostatic field of the main condenser. The two alternating motions thus imparted to the ray being in quadrature, it was made to trace an ellipse on the observing screen of the tube. One could then note the characteristic manner in which the magnitude of the high-frequency voltage varied. The lowest current that could ordinarily be maintained in the oscillating circuit at 123,000 cycles was 3.0 and the highest 12.5 amperes, corresponding to 12.0 and 50.0 kilovolts respectively. The cyclograph indicated unsteady voltage fluctuations amounting to a maximum of 15 per cent, approximately, at 3.0 oscillating amperes. As the oscillating amperes increased, the instantaneous voltage became quite steady, fluctuating less than 5 per cent, maximum. As the current approached 6.0 amperes, producing 24.0 kilovolts, the voltage became quite unsteady. It was always difficult to operate the arc-generator at 6.5 amperes. At such current the hot-band ammeter reading fluctuates and the cyclograph indicates violent fluctuations in the oscillating current and voltage. Persistence of vision frequently caused two concentric cyclograms to appear upon the screen, one corresponding to a current of about six, and the other, seven amperes. Because of this characteristic of the arc no attempt at any time was made to determine sphere-gap discharge voltages at or near 6.5 amperes, corresponding to 26.0 kilovolts. At seven amperes and upward to 12.5 amperes, the cyclograph again indicated steady instantaneous oscillating voltage, whenever the hot-band ammeter in the oscillating circuit produced steady readings.

In making sphere-gap voltage discharge observations the arc-generator was operated and controlled so as to establish a definite high-frequency current in the oscillating circuit. While the sphere gap was shortened slowly to produce the discharge, the ammeters in the main oscillating and voltmeter condenser circuits were read. A set of observations was considered good only when the ammeters gave steady indications. In general, however, under the most steady operating conditions there are some slight and rather rapid fluctuations in the values of the current and, therefore, voltage. The ammeters can only indicate the effective average of such currents and voltages. On the other hand, it is the effective maximums of the slightly fluctuating voltages that actually produce most of the discharges between the spheres. In this manner variable errors are produced in the results, and some strategy is necessary to accomplish

their approximate elimination. These errors always operate to produce apparent voltage values that are smaller than their corresponding true values. For obvious reasons the sphere gap can be shortened only at a slow rate. If it could be shortened at a very high rate and the process stopped at the exact length through which the discharge occurred, all settings would have nearly equal weight in determining the final true result. Under the actual working conditions in this equipment, it is hardly likely that the observed voltages are ever above the true voltages that actually produce the discharge between the spheres. Occasionally, however, the readings of the instruments must correspond much more nearly to the voltages applied to the spheres at the instant they discharge. *The corresponding results will be least in error and must have most weight in determining the final and true relation between voltages and spark gap lengths.*

TABLE I
TYPICAL OBSERVATIONS

Temp. 18 deg. cent. (approx.)				Barometer 30 in. (approx).		
Date	H-B 5-amp. No. 439188 constant multiplier 1.03 0.0001145 m. f.	H-B 1-amp. No. 429926 constant multiplier 1.02 0.0000380 m. f.	H-B 30-amp No. 439113 in main oscillating circuit	Degrees variable capacity (frequency meter180°)= 0.00406 mf. Inductance = 881. micro-henrys	7-in. sphere gaps, inches	Arc voltages gage
1914						
Feb. 5	1.45	0.460	7.90	84.60	0.695	
" 5	——	——	8.00	"	0. 93	—
" 14	1.43	0.456	8.00	"	——	—
" 14	1.50	0.474	8.45	"	——	—
" 14	——	——	9.00	84.5	0.801	48.
" 14	——	— —	9.10	"	0.821	42.
" 14	——	——	9.10	"	0.820	43.
" 19	1.95	0.630	11.20	85.3	1.04	40.
" 19	2.08	0.670	11.80	"	1.03	—
" 19	2.13	0.690	12.20	84.5	1.06	42.

DISCUSSION OF RESULTS

Some of the original observations are given in Table I. The constants of the measuring instruments are also given, so that one may compute the corresponding results for himself. The results obtained are given in Tables II and III and charted

TABLE II
RESULTS

Frequency	7-inch sphere gaps; inches	Kilovolts by instruments
123,000	0.427	20.2
"	0.429	19.8
"	0.452	20.0
"	0.540	24.7
"	0.673	33.0
"	0.693	33.0
"	0.695	32.7
"	0.704	33.0
"	0.738	32.7
"	0.784	35.7
"	0.800	35.8
"	0.811	36.6
"	0.820	37.0
"	0.821	37.0
"	0.863	40.7
"	0.878	40.7
"	1.03	47.5
"	1.04	44.7
"	1.06	48.8
"	1.06	48.0
"	1.09	49.8
"	1.09	49.4
"	1.10	48.5
"	1.10	50.4
"	1.16	51.8

TABLE III
RESULTS

Frequency	7-inch sphere gaps; inches	Kilovolts, by instruments
255,000	0.261	13 500
"	0.253	13.300
"	0.248	13.250
"	0.371	19.060
"	0.378	18.460
"	0.382	18.400
"	0.337	17.670
"	0.404	20.770
"	0.898	43.300
"	0.817	42.600
"	0.886	42.200
"	0.920	42.300
"	0.901	41.900
"	0.931	43.700
"	0.934	44.200
612,500	0.320	14.950
"	0.263	12.300
"	0.285	13.200
"	0.242	12.480
"	0.250	12.200

in Fig. 5. It is noted that the 123,000-cycle values, when the fluctuating character of the source is ignored, locate a right-line relation for the sphere gaps and discharge voltages, and that such line when extended passes through the origin. See curve I, Fig. 5. All values determined at 123,000, 255,000 and 612,500 cycles locate curve II, Fig. 5, when errors due to the fluctuation of the source are largely eliminated.

Curve III, Fig. 5, was drawn for comparison; it was located

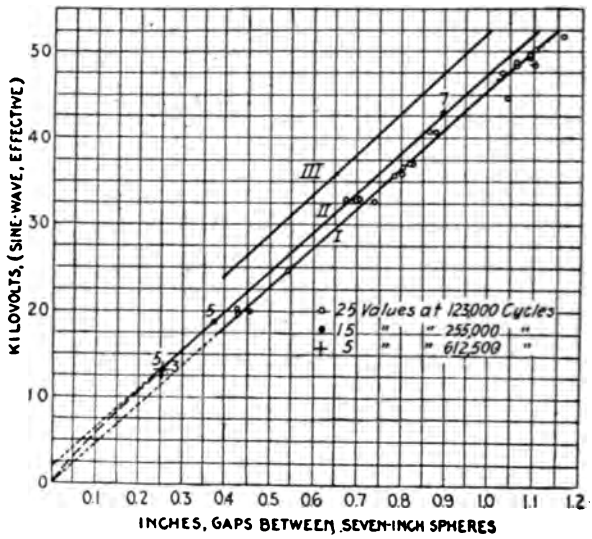

FIG. 5

I. Seven-inch sphere-gap discharge voltage at 123,000 cycles, fluctuations of source ignored. 25 determinations.

II. Ditto. 25 determinations at 123,000 cycles, 15 determinations at 255,000 cycles and 5 determinations at 612,500 cycles. Fluctuations of source eliminated by giving maximum weight to minimum gaps for corresponding voltages.

III. 25-, 37.5- and 50-centimeter sphere-gap discharge voltages at 25 cycles determined by Chubb and Fortescue, Proc. A. I. E. E., Feb. 1913, pp. 635-6.

with the observations made by Chubb and Fortescue for 25 cycles discharge voltages and 25-, 37.5- and 50-cm. sphere gaps. These observations are recorded on pp. 745-6 of TRANS. A. I. E. E., Vol. XXXII, 1913. The high-frequency voltages are almost uniformly 4.5 kilovolts below the 25-cycle voltages. No cause for this difference could be found in our methods of measurements. We believe that both curves have been correctly located.

Conclusions

1. The seven-in. (17.7-cm.) sphere-gap discharge voltages at frequencies ranging from 123,000 to 255,000 cycles per second are given by the expression

$$e = 45.5\, l + 2$$

for the gap range of 0.4 to 1.1 in. (1 to 25.6 mm.), wherein the value of e is in kilovolts, r.m.s., and the value of the sphere gap, l, is in inches at ordinary atmospheric conditions: Temp. 18 deg. cent.; barom. 30 in.

2. Correspondingly at 612,500 cycles per second, 13.06 kilovolts, r.m.s., discharge through a seven-in. sphere-gap length of 0.252 inch.

3. Needle gaps are not practicable for the determination of high-frequency high voltages. The points are promptly melted and burned. Only gaps between blunt points can be employed. For these, No. 14 B. & S. gage, square-ended copper wires were used. The measured voltages were found to be about one-half of the corresponding voltages at 60 cycles.

Acknowledgements

The writers could not have undertaken the present work without special equipment, provided as follows:

Mr. Cyril F. Elwell presented the Department of Electrical Engineering, Leland Stanford Junior University, with a five-kilowatt Poulsen arc oscillating-current generator. Later on the Federal Telegraph Company generously exchanged this generator for a powerful 12-kw. Poulsen-Federal arc-generator, together with a variable condenser and special minor supplies such as litzen draht, carbons and bushings. Invaluable advice and suggestions were rendered in the earlier stages of the work by Mr. Elwell and Mr. Leonard F. Fuller.

DISCUSSION ON "THE SPHERE GAP AS A MEANS OF MEASURING HIGH VOLTAGE" (PEEK), "THE ELECTRIC STRENGTH OF AIR—V, THE INFLUENCE OF FREQUENCY" (WHITEHEAD AND GORTON), AND "SPHERE GAP DISCHARGE VOLTAGES AT HIGH FREQUENCIES" (CLARK AND RYAN), DETROIT, MICH., JUNE 24, 1914.

L. W. Chubb: These three papers presented under the auspices of the Electrophysics Committee are very interesting, and they add a gread deal to our knowledge of high-voltage phenomena.

The paper on the sphere gap by Mr. Peek adds some valuable experimental data on the effect of barometric pressure on the gap voltages. The effect of temperature, however, as expressed in the empirical formula, seems to be a matter of assumption based on free-path and pressure, but not confirmed by experimental data. The inverse proportionality between breakdown voltage and absolute temperature may hold throughout the range of atmospheric temperatures, but the stream of negative electrons from hot metallic electrodes will possibly have a greater effect at high temperatures.

The theories of corona formation and breakdown voltage so far advanced can hardly be adopted as laws until they are more thoroughly tested out, between wider limits.

The formulas given by Mr. Peek agree well with his experimental results, as high as 320,000 volts. Our own direct calibrations with the 25-cm. and 50-cm. spheres agree very well as high as 320,000 volts, with the 50-cm. spheres (one grounded), but above this point the formula and the calculated values given in Table IV do not check with experimental data. For instance, for the grounded case a value in Table IV gives for a separation of 50 cm. a breakdown voltage of 541,000 volts. Direct calibrations show 478,000 when the insulated sphere is freely suspended from a crane and 458,000 volts when both spheres are mounted in the standard frame proposed by Messrs. Farnsworth and Fortescue. The last value given for non-grounded spheres shows a separation of 75 cm. at 725,000 volts. Our direct calibrations show a separation of just twice this gap at the same voltage and without visible corona on the spheres. Below 320,000 volts the points can be reproduced easily, they check the values given in the paper and the sphere gap seems to be a reliable standard for measuring maximum voltage. Above 320,000 volts the gap is unsteady, the strength of the gap is apparently much lowered, extraneous bodies have a greater influence and barometric pressure seems to have a much greater effect than is indicated by the formula. Tests have been made, with one sphere grounded, to voltages over 600,000, and with both spheres insulated, to over 900,000 volts. In the tests there was an increasing discrepancy with voltage increase, between the curves given in the paper and direct calibrations.

At high voltages there is a time effect of breakdown voltage.

Thus at a gap setting of 10 cm. the voltage was quickly raised and the gap broke at 188,000 volts. The gap was then increased one per cent and the same voltage broke over after an application of 55 sec. A second test showed a lapse of 40 sec. The gap was again increased one per cent, and it required 160 sec. for the same voltage to cause a breakdown. Similar effects were shown at other voltages above and below 188,000. At 100,000 volts the effect is inappreciable and below 95,000 volts no time effect could be noticed.

The effect of light is also being investigated and seems to play an important part between terminals which break above the corona point, but, within the range of working voltages, light of ordinary wave lengths has very little effect on the calibration of the sphere gap.

It was thought that the presence of so much corona in the neighborhood of the sphere gap during high-voltage tests might lower the breakdown voltage between spheres. Tests were made blowing air upon the gap from the side opposite to the high-tension apparatus. This air was drawn in a large wooden flume about 20 meters (65 ft.) from the gap and forced with a low-pressure blower across the gap. It was found that the air blast, instead of making the breakdown voltages higher and more consistent as expected, made the behavior more erratic, and caused premature static flash-overs across a gap 25 or 50 per cent greater than the separation required for final breakdown. Several explanations have been put forth to cover this effect, but they need not be mentioned at this time.

The precautions against oscillation given by Mr. Peek are very important, and the damping resistance both in the primary circuit and in series with the gap is very necessary.

The paper by Messrs. Whitehead and Gorton is certainly an example of a good record of the work done. After reading such a paper, one feels that he has no questions to ask why, how or under what conditions the several steps were followed out.

The vibration of the wire at high frequencies seems to prove that the wire was well centered. A stroboscopic view of the vibrating wire would probably show the wire to be vibrating at its natural period with an increased corona on the side of the wire in the direction of the instantaneous deflection. This corona causes the familiar electric wind, the reaction of which tends to restore the wire to the center. A possible explanation is that due to the lag of corona formation upon the deflection of the wire there is a greater force acting on the wire when it is traveling toward the center than when it is traveling outward, which would cause a sustained vibration.

The three possible explanations for the effect of frequency on corona formation, given on the last two pages of the paper, seem to indicate that at high frequency the appearance of corona would be at an increased voltage, while the results show the reverse effect.

All the papers show discharge at a lower voltage at high frequency, and the authors are certainly to be congratulated on this agreement. The discussion over a year ago which probably stimulated the frequency tests, contains several statements that the gap would be stronger at high frequency. The new records show clearly that direct tests rather than theories should be used to study such complex phenomena.

F. C. Caldwell: Would there be any chance for error due to the drop in the high series resistance, especially at high frequencies, or would the fact that the charging current is out of phase eliminate any such error?

D. M. Mahood: Referring to curves of Fig. 5, in the paper by Messrs. Clark and Ryan, showing discharge voltage for high frequency as almost uniformly 4.5 kilovolts below the 25-cycle voltages, it is suggested that this is due to the fact that pure undamped waves were not obtained during these observations. With about 10 to 15 ohms high-frequency resistance for the inductances L_1 and L_2 in the oscillating circuit, about 8 ohms high-frequency resistance for the carborundum safety resistance rods in series with the sphere gap, and about 2 ohms operating resistance of the arc itself, there exists a decrement of apparently 0.02. The cyclograph used, indicating only the r.m.s. value of potential existing, permits the periodic high swinging potential which breaks down the gap to slip by without being taken into consideration during observations.

The conditions existing during tests indicated in the first paragraph of the second page of the paper, showing 17.6 amperes direct current about equal to alternating current (12.5 r.m.s. or 17.6 maximum value) in the arc, are extremely unstable. Our experience with Poulsen arcs has shown that where such conditions exist there is considerable fluctuation of voltage and other conditions of the arc. With this maximum voltage value jumping up at times and not possible of indication on any of the instruments used, the discrepancy between the 25-cycle and high-frequency curves may result.

The best oscillating arcs constructed and specially designed for stability for measuring purposes (those of Lindemann, duplicating those of the German Reichsanstalt,) gave 2 per cent variation in amplitude at 133,000 cycles. Methods for standardized calibration making use of the oscillating arc are capable of too much error, caused by the instability combined with the occasionally swinging high-amplitude wave, and should not be considered conclusive until an opportunity is afforded to check the high-frequency results under more stable conditions, using high-frequency generator with absolutely constant speed maintained.

Charles Fortescue: Discussing first Mr. Peek's paper, the results of the tests under various atmospheric conditions, pressure, frequency, etc., are a valuable addition to our knowledge of the subject. It is gratifying to find that these tests

agree with theoretical figures, as far as they have been carried out. Mr. Peek's tables of spark-over voltages add nothing to the data already available on the subject, except in confirmation of the results obtained for 25-cm. spheres, with smaller spheres. On the contrary, Mr. Peek's assumption of constant apparent potential gradient at spark-over, for a given sphere, based on his assumption that this quantity is the same function of $\frac{x}{r}$ as the true intensity, leads to no useful result, and in my opinion beclouds the real issue. We are confronted with two problems: first, the calibration of sphere spark gaps of various sizes; second, determination of the theory of the voltage breakdown of the spark gap.

The old theory propounded by Russell has been found not satisfactory. Mr. Peek has evolved a theory of the effect of shanks. I do not think that the discrepancy can be attributed to the shanks. The shanks have very little effect on the breakdown voltage. I think it must be due to some other cause, and in attributing it to the effects of shanks, we are losing sight of the real issue and preventing ourselves from finding out the real reason of the discrepancy.

We have been working on the calibration of the spark gap in Pittsburgh, and as Mr. Chubb states, we have carried calibrations on a grounded 50-cm. spark gap from potentials of 300,000 volts up to 600,000 and above. In making measurements of the maximum value, we use the condenser terminal as a condenser. The condenser terminal is an excellent condenser. We judge from our experiments that the effect of the external bodies on the capacity can be made extremely small.

In our measurements there was no corona present on the terminal itself, under any of the measurements, except on the small choke coil on the top of the terminal. The wire leading to the spark gap had considerable corona, a soft glow without streamers. There was a certain amount of corona on the resistance leading to the spark gap and on the bushing through which the shank of the spark gap passed. It may be that in making our measurements by means of this condenser, and averaging the value of the charging current with the condenser method, there are oscillations set up due to corona disturbances, which, of course, take place at the peak of the wave, which may not be taken into account in the average value of the charging current of the condenser, so that it is possible that the effect of the corona in the wires, etc., vitiated our tests slightly. But I do not think that this can account entirely for the large discrepancy between the theoretical figures and the figures obtained by test. It seems to me that the lower breakdown spark-over voltage of large spheres, as compared with small spheres, must be due to some external effect. Perhaps it is a question of free ionization in the air; it seems probable that the largest sphere collects

its electrons and positively charged molecules from a very much larger volume of space than the smaller spheres. The positive charges will be drawn toward the electrode that happens to be negative at a certain instant, and the negative will be drawn toward the positive. While these charges do not cause immediate breakdown, their presence will increase the intensity at the surface, they will tend to accumulate at the point of highest potential gradient and finally, on the largest spheres, increase the intensity sufficiently to cause spontaneous ionization.

Referring to the paper by Messrs. Whitehead and Gorton, their modification of the method first used by Mr. Chubb and myself, to meet the exigencies of the high-frequency test, is very interesting, but there is a question in my mind whether the rectifier does not produce superimposed oscillations of its own. In other words, as I see it, in their circuit they introduce what amounts to a square-topped alternating wave which has an infinite number of frequencies. It is possible for conditions to arise such that any one of this infinite number of harmonics may resonate, causing a high peak in the voltage; which may be of such frequency and characteristics that its true value is not properly recorded.

Another possibility of error suggests itself to me in Dr. Whitehead's tests. I do not think it safe to assume that the rotating field of the generator has sufficient inertia to prevent it from causing troubles due to surges in the supply circuit. Our experience in the first calibration of the sphere spark gap showed that even with an armature running at very high speed, supplying alternating current to the testing transformer, the effect of surges in neighboring circuits was noticeable—we had a neighboring three-phase grounded crane circuit, in which heavy loads were suddenly applied, and we found this had a great effect on our testing voltages. Every time the crane hoist started, we would have a breakdown and oscillation, in spite of the fact that the two systems were connected only through mechanical parts having considerable inertia. The reason, as I understand it, is that any slight oscillation in the mechanical part will set up an oscillating voltage, which may in itself be small, but under certain circumstances the oscillation may have the same period as the test circuit, and cause quite high oscillating voltages.

Probably either of these two possibilities may explain the results that Dr. Whitehead found—namely, that at certain definite points there was an apparent discontinuity in the corona point.

In connection with the question of resonance in transformers, we had some experience which led us to try to find some way of getting an absolute method of measuring maximum voltage without having recourse to ratio. Our shop testing force had an experience several years ago with a high-voltage transformer

which was to be tested for certain overload capacities. They could not get the transformer past the testing floor. Every time they tested it by the ratio method, they failed. For some reason or other it never occurred to them to use the sphere gap to find out what was the trouble. I was asked to go down and investigate the matter. I suggested that we try to see what the sphere gap showed. We found in the case of one generator a test value above that shown by ratio all the way from zero to 60 per cent on the high-tension side, purely due to wave distortion and resonance of the distorting harmonic. It is never safe to trust to ratio on tests with very high-voltage transformers, on account of the fact that the capacity of the transformer is necessarily quite large.

Referring to the paper by Messrs. Clark and Ryan, I wish to ask the authors if they assume that the wave form of an oscillating circuit is so close to a sine wave that it cannot affect the maximum value of the voltage. We have had waves of applied voltage that looked like almost perfect sine waves, which gave waves of charging current with condensers which showed distinct harmonics. The multiplying factor of the higher harmonics is very large, so that even a very small fraction of a normal frequency would be magnified and multiplied, through resonance, enough to have a large effect on measurements, resulting in large discrepancies from the values indicated by ratio.

I note another thing in the paper by Messrs. Clark and Ryan, and that is that their spheres are isolated, and they have no distinct zero potential point in their system. In such a case we have no idea what the relative potentials of the spheres are. The whole system may oscillate at a high frequency above zero, so that the maximum intensity at the spheres of such a system is quite indefinite. For that reason, I am inclined to think that these tests cannot be considered as final.

A point Messrs. Clark and Ryan bring out in their paper, which I think is very important, is the question of the weight to be given in test measurements in connection with such a piece of apparatus as the spark gap; the sphere gap particularly. In studying the sphere gap, it has a maximum breakdown, which is the voltage we wish to arrive at. Our tests are possibly subject to extraneous conditions, such as surges in neighboring circuits, etc., and also to fluctuations, breakdowns due to the oscillation and consequent fluctuation, but if measurements are carefully carried out, it is not possible to obtain values higher than the actual breakdown voltage. So that in using the results of such tests the average of a large number of tests is not necessarily the correct value, but rather greater weight should be given to the maximum values, in other words, any discrepancy will be of lower value than the actual true strength, and is probably due to the oscillation or some trouble in the circuit itself.

Referring to the maximum voltage meter, as I have called it—the method that Dr. Whitehead has used and which Mr. Chubb

and I used in the original paper on the calibration of the sphere gap—I may state that it gives what may be called the average maximum value. In other words, it cannot show the maximum value that may occur at any one cycle, due to some external effect; if there is a difference in the positive and negative wave form, or change, during a very short length of time, this cannot be shown. It simply indicates the average of a consecutive series of waves of charging current, and gives the average maximum value of applied voltage for the consecutive series. In order that this shall be the true maximum value, it is necessary to presuppose a steady and constant applied voltage and a constant secondary voltage.

The vibration of the suspended wires, mentioned in the paper by Messrs. Whitehead and Gorton, I have also observed at corona points on wires with neighboring large bodies.

D. D. Ewing: I believe we all realize that one of the greatest difficulties we have to encounter in the study of high-tension phenomena is the difficulty of making the measurements with any degree of scientific accuracy. The points I have in mind were brought up by Dr. Whitehead's paper. I believe Mr. Fortescue, if I understood him correctly, touched on one of them, namely, the deformation of wave form when the mercury arc is used as a rectifier. I notice that Dr. Whitehead in his experimental work made use of a direct-current measuring instrument, presumably of the permanent magnet moving coil type. He states in his paper that the permanent magnet type instrument is suitable for the purpose although he does not specifically state that he made use of this particular type of instrument. I would like to call attention to the fact that some of the common commercial forms of this type of instrument can not be relied on to give a very high degree of accuracy, when used to indicate the average value of a fluctuating quantity. In some tests made several years ago, on some meters used in railway service, I found that the average value was about 15 per cent off. In the measurements made by Dr. Whitehead, the errors introduced by the use of the mercury arc and this type of instrument would be differential rather than cumulative, thus giving a low resultant error. I wish, however, to call attention to this fact about the direct-current permanent magnet instrument: it must be used with caution if the quantities are fluctuating rapidly.

E. E. F. Creighton: I think the most evident thing in all these papers and in all the discussions which have taken place in the past few years has been the lack of some instrument or some device that will accurately measure the voltage. If such an instrument were available at the present time, the whole subject could be cleared up.

Every one of these papers adds a little more, makes one step nearer the final solution, by giving the results of some method which has been tried out for the measurement of voltage at high

frequency. We have endeavored in the study of lightning arresters for many years to get something we could rely on. Our endeavor has been, not so much to locate a condition and measure the voltage, but to vary all the conditions and get the minimum gap length as near as we could for the same voltage impulse applied.

In working with Alexanderson's alternator, running up to 200,000 cycles per second, one of the first difficulties encountered was the impossibility of getting any definite voltage ratio in the transformer. We had a transformer made up of eleven layers, and used one layer as a primary and the other ten layers as a secondary, stepping up 1 to 10. We found at a certain frequency when 100 volts was applied to the primary we got 100 volts across the secondary. Instead of getting 1 to 10, according to the ratio of turns, we had a ratio of 1 to 1. Then we took our voltmeter and applied it to the different layers, and found one layer that was given a ratio of ten times the impressed voltage, in other words, 1000 volts, where the ratio of the number of turns was only 1 to 1. This simple illustration shows the effect of internal capacity in entirely changing the voltages that should be given by the ratio of the number of turns.

In regard to the free ionization in the air, we have had by tests in the laboratory a number of illustrations of this ionization effect. The vacuum arrester consists of a copper tube with an insulated electrode on the inside and more or less vacuum produced around these electrodes, depending on the spark voltage desired. The gap length is of the order of 1 mm. and the diameter of the tube only about $\frac{3}{4}$ in. (about 19 mm.). When potential is first applied the sparking voltage may be 500 volts. If potential is applied immediately afterwards a lower value is needed to cause a spark—even as low as 350 volts. It requires considerable time, a number of minutes, in some cases a number of hours, for this internal ionization to disappear.

Another case of ionization was illustrated in the test we showed before the Institute something over a year ago, in which we recommended the use of high frequency for the testing of insulators. It is shown in all of these tests that when high frequency is applied to an insulator there are obtained many sparks that are fairly evenly distributed around the surface of the insulator. These sparks are not simultaneous, but successive. The explanation of the distribution may be that when the potential is applied to the cap of the insulator it ionizes more or less evenly the atmosphere all over the surface of the porcelain. Due to accidental conditions, the first spark will break over at some one point. In so doing, it will relieve the stress in the atmosphere at that point. The subsequent sparks will find points in the atmosphere elsewhere that are highly ionized and the subsequent sparks will consequently take other paths. I think this is another illustration of the fact that ionization may reside for a considerable time in the atmosphere.

Professor Caldwell brings up a very pertinent question, that is, in using resistance in series with spark gaps, is the testing outfit still applicable for the testing of apparatus? While series resistance is desirable as recommended, there is a special condition where it is not applicable. It is not applicable to the testing of lightning arresters. A series resistance of one ohm per volt will give erroneous results in the testing of arresters. We have used for many years without series resistance a transformer at 100,000 volts for testing work, and in only two cases during all that time have oscillations been produced which damaged the end turns.

Mr. Peek has brought out definitely that moisture in the atmosphere causes an increase in the spark potential of a needle gap (but not of a sphere gap).

It may be of some interest to note that in the testing of multigap lightning arresters the opposite effect is sometimes found. For example, a compression chamber lightning arrester tested on a perfectly dry day had a certain sparking potential. Three days later on a humid day and without any changes in the circuit the spark potential was considerably lower. From a certain point of view, that is a valuable thing to know. When lightning is about to take place, the arrester will be a little more sensitive.

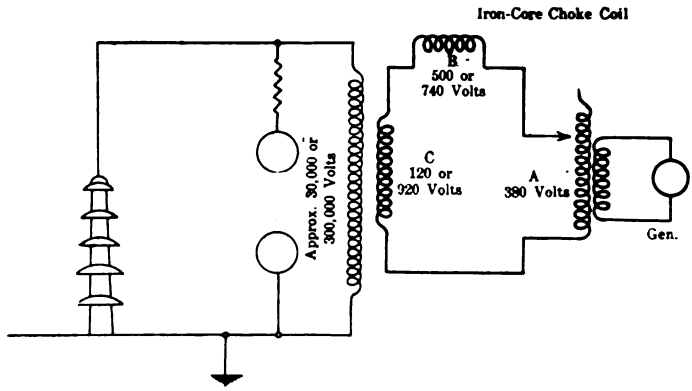

FIG. 1

H. B. Dwight: In Mr. Peek's paper are given various precautions to be observed in making high-voltage tests. Although the list was not meant to be complete, I would suggest adding to these the avoidance of the use of choke coils with iron cores, even in the low-tension circuit. There is a tendency to use such coils in practical testing because small transformers or autotransformers are generally available in many sizes, while air coils are not. The iron-cored coils may not always produce trouble, but there is distinct danger of it, as is shown by the following experience encountered in routine commercial testing.

In testing some insulators at 300,000 volts, an iron-cored choke coil was used as at *B*, Fig. 1. On applying a low-tension voltage

which normally gave about 130,000 volts, an entire absence of corona was noted. On again closing the switch with exactly the same connections there was a heavy continuous discharge over the insulator, indicating much more than 130,000 volts. Repeated closing of the low-tension circuit gave sometimes one and sometimes the other of these two steady conditions.

In locating the cause of this trouble, it was found by measurements of the voltages on A, B and C that the voltages on the insulator in the two steady states were about 30,000 and 300,000 and that the choke coil was in the one case unsaturated and in the other case, saturated. Which state was produced depended apparently on the part of the voltage wave at which the circuit was closed. Both states were steady except that sometimes the first would suddenly change into the second, with corresponding increase in voltage.

The vector diagrams for the two different steady states with the same applied voltage of 380 volts, are shown in Fig. 2.

An indication of how the saturation of the iron core produces

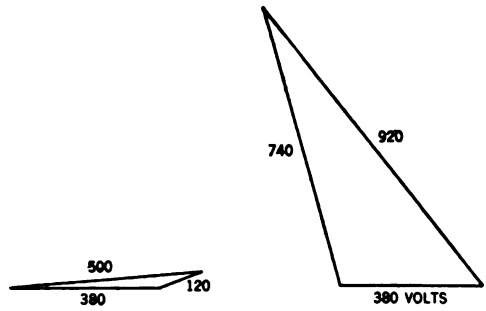

FIG. 2

the erratic results is shown in Fig. 3. The curve of applied voltage is to be calculated from the capacity of the insulator and the magnetizing current and iron loss current of the choke coil. For details of this calculation see the *Electric Journal*, p.1102, December, 1911. The current and voltages have been observed with an oscillograph and have been found to have the same frequency as the generator, and to have phase relations in agreement with the vector diagrams.

The phenomenon is essentially a low-voltage, standard frequency phenomenon of continuous duration. It has no connection with the high-frequency oscillations which occur around a spark gap and it is quite distinct from the phenomenon of simple resonance. The two different voltages obtained from one connection of apparatus depend on the combination of leading current and an iron magnetic circuit which becomes saturated. It is seen, from Fig. 3, that a certain value of applied voltage may correspond to two different values of amperes, according to a point in the part $U\ R$, or the part $T\ S$, of the curve for applied

voltage. These two values produce two different values of voltage on the testing transformer, the curve for which is seen to be in two parts, separated by an unstable region.

In investigating this phenomenon, the applied voltage may be slowly increased from U to R, and then the current will suddenly change from R to S. Thus, about ten times as much current will flow through the choke coil, and a high voltage will be produced. Then, on lowering the voltage gradually from S to T, the current drops suddenly from T to U, and the original condition is obtained.

Since a choke coil with an iron core may render indeterminate the voltage to be obtained from a given arrangement of appara-

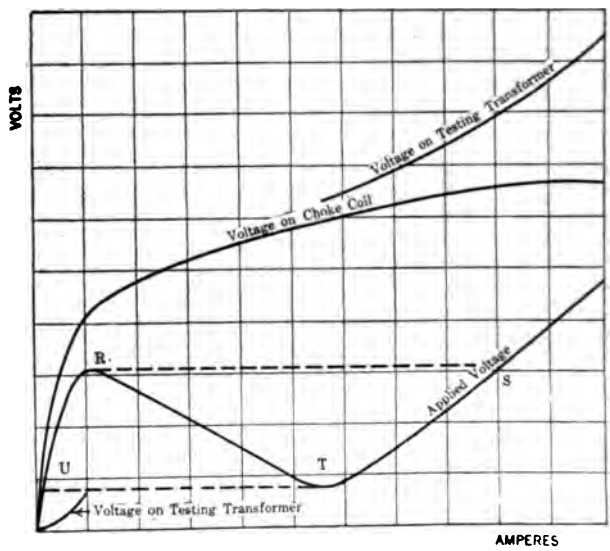

FIG. 3

tus, and may give suddenly a far greater voltage than would be expected, its use would appear to be inadvisable.

W. W. Lewis: Mr. Peek says that carbon or graphite rods should be avoided as resistance in series with the sphere gap, because they are unreliable. We have found in Pittsfield that this is usually true with the so-called "high-rated" carbon rods, that is, rods that are rated in the neighborhood of 60,000 ohms each, because these rods contain very little carbon; they are composed of some kind of clay mixed with graphite, and their resistance changes when current is passed through them. The "low-rated" rods, *i.e.*, rods rated in the neighborhood of 4000 ohms each, we have found to be very constant and reliable. We have checked these by measuring the voltages set up in the high tension of the transformer under test, when the spark gap

is arced over as shown in Mr. Peek's Fig. 13, and we find that we get no appreciable voltage set up in the high tension of the transformer when resistance is used to the value of one ohm per volt or over. We have also run heat tests on these rods and find their resistance to remain constant, whereas that of the high-rated rods increases appreciably.

We have tried metallic resistance and find that in order to get high resistance, very small wire must be used, and to prevent this burning out, it must be immersed in oil. It is very difficult to prevent the oil from leaking and to insulate the resistance properly. Water resistances are subject to the trouble that steam forms at the terminals and the water explodes violently from the tubes. We have decided that, altogether, the low-rated carbon rods are nearest to the ideal.

Mr. Peek in his precautions says: "The spheres should be twice the gap setting from surroundings." It is rather indefinite as to just what this means. We have interpreted it at Pittsfield to mean that no part of the wooden supporting standard or metal shank bushings shall be nearer to any point of the spheres than twice the maximum gap length. When you figure on 75-cm. spheres, which we have at Pittsfield, and allow a distance of 150 cm. from the supporting standards to the spheres, and 75 cm. as the maximum gap, this gives 525 cm., or about 17 ft., between sphere gap standards, and this means a great expense in treated wood and in floor space.

I understand that the new Institute rules are more lenient in this respect, reading that "No extraneous body or external part of the circuit shall be near the gap within twice the diameter of the spheres." With the 75-cm. spheres, the distance between standards would be, according to this rule, 375 cm. or about 12 ft. The rule might well be further modified, a distinction being made between bodies that are insulating, and metallic bodies.

We have made a few tests recently to check the effect of wood, metal and porcelain on the sphere gap arc-over, when these objects are placed at different distances from the spheres, and we find that wood and porcelain have practically no effect when placed as close as one-half the gap distance away from the spheres. Metal; however, appreciably reduces the spark-over, that is, when a sheet of metal was placed one and one-half times the gap distance away from the spheres, the spark-over voltage was reduced four per cent.

Mr. Fortescue questioned the statement in regard to the effect of metal on the shanks. To check this we made some tests, placing a disk of a diameter equal to the diameter of the sphere (12.5 cm.) on the shanks at different distances from the sphere, and we found that when this disk was placed on the shank of the non-grounded sphere (these tests were all made with one sphere grounded) it made as high as 3 per cent difference in the spark-over. These values were checked several times,

the voltages being determined by a voltmeter coil placed in the center of the high-tension winding of the testing transformer. We have found the voltmeter coil to be very accurate and valuable for this kind of work.

E. P. Peck: I want to ask Mr. Peek what he meant by saying, on page 945, "For steep wave fronts a higher voltage is required to spark over a given gap than for low frequency." The rest of the paper indicates that the higher the frequency the lower the spark-over. This one remark indicates the other direction.

J. R. Craighead: A previous speaker mentioned the practise of using the voltmeter coil in the middle of the transformer as a means of reading the voltage, and at the same time spoke of using one of the spheres as grounded. Now, it sometimes becomes convenient to ground the transformer in the middle when the voltmeter coil is there, to protect the voltmeter coil. I would ask Mr. Peek if he can tell us anything about the relation of this to the grounded curve and the ungrounded curve. Also, what is the effect of the ground placed at some other point in the circuit?

F. W. Peek, Jr.: Mr. Chubb states that after a given high voltage is reached, spark-over will result between spheres, no matter how far the gap length is increased. In other words, the law which I have given suddenly ceases to hold. The curve becomes discontinuous.

Theory at once explains this discrepancy, when the cause may be readily corrected or removed in *practise*. The curve is really continuous. The reason for the discrepancy is as follows:

The spheres with their connecting leads make up a circuit of capacity and inductance. A local spark-over or static spark on a section of a supporting bushing, from the end of a connecting wire, etc., will cause a readjustment of energy distribution in the circuit. An oscillation or high transient voltage results, which is superposed upon the applied voltage and causes the sphere gap to spark over. The actual voltage at the sphere gap may thus easily be double the applied voltage, or the voltage read at the meter. The sphere gap may thus, under this condition, be lengthened out to a considerable extent, or to the limit of the transient voltage, and spark-over will result. The sphere measures the transient voltage and not the applied voltage. The applied voltage at which the curve appears to become discontinuous, is the critical voltage for local breakdown somewhere, as on leads, etc. The transient follows. The effect may be easily reproduced in the laboratory at fairly low voltages. It is more likely to occur in practise at high voltages because static sparks are most likely to occur at high voltages. The remedy is to arrange leads and conductors so that local static sparking does not occur and so that the gap supports are insulated to withstand the voltage to be measured. The resistances should be placed directly in series with the gap and as near the

spheres as possible. The sphere gap is much more sensitive to transient voltages than the needle gap. Care must always be taken to prevent these voltages reaching the gap, unless it is desired to measure them.

As an example: A sphere gap without series resistance was placed in parallel with a string of insulators, and voltage applied. The known arc-over of the insulators was 300 kv. The sphere gap was set for that voltage. At 295 kv. static sparks occurred on the insulator unit near the line end. The sphere gap sparked over, due to the resulting high transient voltage, and relieved the pressure. The gap was lengthened. At 295 kv. the transient again occurred and caused the sphere to spark over. It was in this way necessary to increase the sphere gap to a spacing equivalent to 400 kv. before the insulators sparked over. The spheres in this case measured the transient voltage. In such tests it is preferable to use the spheres only to calibrate the wave shape and transformer ratio. This should be done at a voltage below that at which static sparks appear on the insulator.

We have, since the paper was written, actually checked a calculated curve for 75-cm. spheres up to 700 kv. with good agreement. It was, of course, necessary to use a very well insulated stand and leads, etc., at this voltage.

The effect of altitudes must be the same at high voltages as at low voltages. At high voltages the spacings are greater than at low voltages; the resulting gradients upon which the breakdown depends are the same. In my former papers I have shown that the decreased strength of air at high altitudes is the result of decreased air density, and that the effect is the same whether the change in density is due to temperature or to pressure.

Mr. Dwight's discussion is interesting. I should like to see the data.

The term "high frequency" is at present very loosely used and under it are included continuous high frequency, and transient voltages, as oscillations, steep wave front impulses, etc. The effects of these are naturally quite different. There are, in this way, many apparent discrepancies in the effects resulting from the "same" cause—"high frequency." The term is thus used to explain many "mysterious" failures. The sphere gap, when the maximum spacing is limited to the diameter of the spheres, measures with fair approximation high frequency, and transient voltages. In case of high frequency care must be taken to polish carefully the surface of the sphere. The needle gap does not even approximate such voltages. At continuous high frequency the needle gap curve is changed by the intense local heating; at steep wave front by the limited time. This is discussed in my paper. I have given a theoretical explanation in former discussions.* It may be of interest to give an example of impulse voltage here:

*Page 138, this volume.
"High Voltage Engineering", *Journal* of Franklin Institute, Dec. 1913. Page 612, this volume.

Spacing of Needle cm.	Voltages Required to Cause Needles to Spark Over			Ratio	
	60 cycles max.	Impulse voltage (measured by 25-cm. spheres, using 60-cycle curve)	Impulse voltage calculated from circuit constants	Calculated impulse voltage / 60 cycles	
				Needles	Spheres
2.3	26.0	36.6	39.5	1.41	1.08
3.95	39.5	59.5	60.5	1.45	1.02
5.34	51.5	73.5	74.5	1.45	1.01

A higher impulse voltage is required to cause the needles to arc over than at 60 cycles. The spheres arc over at approximately the same voltage at 60 cycles and impulse. This particular impulse reached its maximum in 0.00045 milliseconds. A steeper impulse would require a still higher voltage on the needle gap to cause arc-over; with continuous high frequency the needle sparks over at lower voltages than at 60~. Great caution is thus necessary in making "high frequency" tests. Much damage may also be done to apparatus, etc., as I have pointed out, unless tests are made with caution. Care should be taken to place the spheres at a considerable distance from ground and from large metal or other conducting masses. In no case should this distance be less than twice the sphere diameter. This is so whether both spheres are insulated or one sphere is grounded. The curves for both spheres insulated were made with the neutral at mid-point. To be sure of this, it is desirable that the transformer neutral be grounded. Carbon rods may be made in which the resistance is not greatly affected at high voltages, but rods as generally made are affected.

Dr. Whitehead has developed an extremely interesting method of measuring high-frequency voltages. I have also noticed the phenomenon of vibrating wires which Dr. Whitehead mentions. Photographs showing this are given in my 1912 paper.

Referring to Fig. 5, in the paper of Messrs. Clark and Ryan, I would like to call attention to the fact that at small spacings the 60-cycle curve is also approximately a straight line. At higher voltages the high-frequency curve will bend as the 60-cycle curve does. For 7-in. (17.8-cm.) spheres, curve III will fall closer to I and II.

John B. Whitehead: It is interesting to ask, in connection with this question of frequency, to what conclusion these papers lead us. Considering the ascending range, there is evidence from our experiments that with increasing frequency there is a

slight, but certainly evident, lowering of corona-forming voltage. There have been one or two suggestions, by Mr. Fortescue and others, of possible sources of error, and at first glimpse it appears that these errors, if they exist, would be in the direction of lowering the apparent corona voltage. In my opinion, however, these errors are not present.

In Mr. Peek's range of frequency, up to 40,000 cycles, a further lowering is indicated; and then going up to the maximum range, Professor Ryan has a still further lowering. In the case of oscillating circuits, long associated in our minds with brush discharges, it would not be an astonishing thing to find that at higher frequencies we would have lower corona-forming voltages. At the same time, high values of peak voltage which cannot be detected often occur in oscillating circuits, so it is not necessarily the case that we must have a lower corona voltage in a high-frequency circuit, simply due to the higher frequency.

In Mr. Peek's description of the experiments at 40,000 cycles, he suggests that if his spheres had been more carefully cleaned he might have gotten a discharge voltage which would be more nearly that observed at commercial frequencies. He also measured his voltages, as I understand it, with an electrostatic voltmeter. Although he states that correction has been made for wave form, the static voltmeter measures effective values, and it would be interesting to know how he has applied correction at these frequenceis.

The observations reported in the paper by Messrs. Clark and Ryan, as to the ratio of lowering at still higher frequencies, show a remarkable lowering of corona voltage. It is to be hoped that Professor Ryan will repeat some of his interesting experiments and corroborate the present results beyond question.

Summing up the three papers, there is a distinct evidence of lowering of the corona voltage with increasing values of the frequency. The amount of that lowering is apparently small, except possibly at very high frequencies. For these high frequencies more observations are desirable.

With reference to Mr. Fortescue's suggestions as to possible errors in our observations due to the presence of the mercury gap and the inertia of the generator, we did not use the mercury arc itself as a rectifier. Our two mercury arcs were excited by independent continuous-current circuits, and we had the auxiliary electrodes in the mercury tube, simply using the very copious ionization which is always present in a mercury arc as a conducting path which had, of course, only unipolar conductivity. The very small current carried, and the fact that the tube was in series connection, indicate oscillation as a very remote possibility. At the same time, the suggestion is possibly an explanation of the unstable conditions in the region near 400 cycles where we found evidence of resonance.

The inertia of the generator was simply mentioned as one of the factors which led us to believe that we had stable conditions,

conditions which were uniform at all times, and our observations were repeated so definitely throughout that there is hardly a chance for error on account of the possible fluctuation of the mass of the armature.

In reference to Mr. Ewing's comment on the possible error in using a permanent magnet type of instrument for recording average values, this type of instrument has been used for taking average values ever since the days of the first contact makers for measuring wave forms. It would be interesting to know for what range of pulsations Mr. Ewing made his observations. We are, of course, working here up between one thousand and three thousand cycles, far above the highest commercial frequencies.

Before closing the meeting, I would like to report an experiment which has recently been made abroad, the news of which has come to me in a letter. It is a matter of very great interest and with your permission I will take about five minutes to tell you about it. There has been no official publication of it as yet, but the publication will follow, and the word that comes to me from one of my colleagues who was present, and saw the experiment, is what I wish to report to you.

We are all familiar, of course, with the mechanical analogies that are drawn between electric circuits and the motion of masses, in which we consider inductance as mass, capacity as elasticity and resistance as the friction in a mechanical system. If we follow this analogy, and hark back to one of Newton's laws, that a body will persist in its state of motion unless acted on by some external force, it will explain the experiment in question. If we could realize mechanically the motion of a body absolutely free from all friction, the body would go on moving indefinitely.

Professor Kamerlingh-Onnes of Leyden has produced the current which does not die out, and which is not excited by any electromotive force, thus realizing the analogue of the moving mass free of all friction. The experiment is briefly this: He takes a coil of fine lead wire of about 1000 turns, and about 2 cm. in diameter, and short-circuits it on itself. This coil is placed in a strong magnetic field, the lines of force threading this round coil. A vessel of liquid helium is brought up so that the wire may be immersed in it, while still remaining in the magnetic field. The liquid helium sets up temperatures which are far lower than any temperatures we have known, even lower than the temperatures that may be got from liquid air and liquid hydrogen, temperatures which are at least in the neighborhood of the absolute zero. If you take curves showing the relation between the specific resistances of materials and temperature, these curves for all substances are all straight lines and all tend down to the absolute zero, indicating that the resistance would become zero if the temperature were extended to the absolute zero. The liquid helium brings us nearer to it than

we have ever been before. Now, with the helium, we have a coil of lead wire in a strong magnetic field, and at a temperature, we will say, in the neighborhood of absolute zero, minus 273 deg.

Under these circumstances the circuit of the exciting magnet is broken, inducing an electromotive force and consequent current in the short-circuited coil, which is near absolute zero, and therefore near zero resistance. Consequently, there is no frictional element, no damping factor, if you please, and the current should go on indefinitely since the coil has no resistance. It went on during a period of four to five hours, which was stated as the time of observation of my friend. There was no indication of a diminution of the current in that coil at the end of from four to five hours.

M. G. Lloyd: What was the evidence that the current was continuing?

J. B. Whitehead: It was not stated. The exciting circuit was broken, and the exciting magnet removed. I should imagine the evidence would be the influence of the coil on a magnetometer needle. It seems the most obvious way.

W. B. Kouwenhoven (communicated after adjournment): The three excellent papers presented under the auspices of the Electrophysics Committee all had to do with high voltages, and in all of them the accurate determination of the voltage plays a very important part. I wish to bring to the attention of the members a method for measuring the effective value of alternating-current voltages, which has a very high degree of accuracy. This method consists, briefly, in using a high resistance connected in series with a small resistance across the high-voltage terminals, and measuring the drop of potential across the small resistance with a quadrant electrometer.

Suppose that a high resistance R and a small resistance r be connected in series across a potential difference of V volts, and that the drop of potential across the small resistance is v. Then $V = \frac{R + r}{r} v$. This method, when used for direct current and low voltages, is simple and accurate. When applied directly to alternating currents and high voltages, however, it is no longer accurate, because of the capacity currents which flow not only from the resistances to earth but also between the different parts of the resistances. On account of this the current passing through the resistances can no longer be considered as quasi-stationary; the ratio

$$\frac{V}{v} = \frac{R + r}{r}$$

holds no longer, and the voltages in different parts of the resistances are in phase neither with each other nor with the total voltage. It is possible, however, so to construct the resistances that the inaccuracies are eliminated.

Let us consider such an arrangement of resistances theoretically. Suppose that the large resistance be divided up into n units or divisions R_1, R_2, R_3, ... R_n, and that these are so small that we may consider the current in each to be quasi-stationary, and that the current in going from division to division changes slightly in value and in phase. This arrangement is illustrated in Fig. 4. One terminal of the high voltage is connected to the resistance division R_n and the other to R_1 and at the same time to earth. Now in R_n the capacity currents to earth are the largest and these currents are ahead of the total voltage in phase. Therefore the voltage drop v_n in this resistance unit leads the total voltage V. The voltage drops in the various resistance divisions and the total voltage form a polygon as shown, and it follows that the voltage drop in R_1 lags behind the total voltage. Voltage measurements are

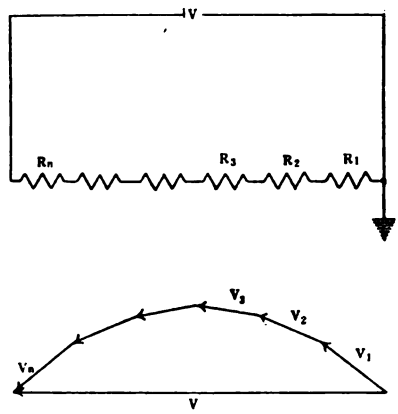

FIG. 4

usually carried out at the earthed pole and the problem resolves itself into bringing the current and voltage in R_1 into phase with the total voltage, and in determining the value of the ratio between V and v.

A set of eight resistance units based on this principle was built in the laboratories of the Reichsanstalt, Germany. The German resistance units were wound with manganin wire; the maximum voltage drop per unit, without over-heating, was 3000 volts. I built a set of resistance units using a liquid resistance as a substitute for the wire resistances in order to determine if, by so doing, it was possible to increase the voltage range of the apparatus and to use an electrolytic resistance for this purpose. The electrolyte was the so-called Manganini solution, and proved very successful.

Each resistance unit consists of a Jena glass tube which contains the solution. These tubes are about a meter in length,

have a diameter of approximately 1 mm. and are fitted with expanded ends to allow room for the electrodes. With tubes of these dimensions it is possible to construct a resistance unit of 24 million ohms per meter length. In order to define the capacity to earth, each tube is fitted with a metal cylinder slightly longer than the tube and of 10 cm. inner diameter. These cylinders are well insulated from the Jena glass tubes and the entire arrangement may be regarded as a cable whose central conductor has a high resistance per unit length. In order to bring the current at the earthed pole into phase with the total voltage V, it is necessary to apply a voltage to the metal cylinders such that there will exist a certain definite difference of

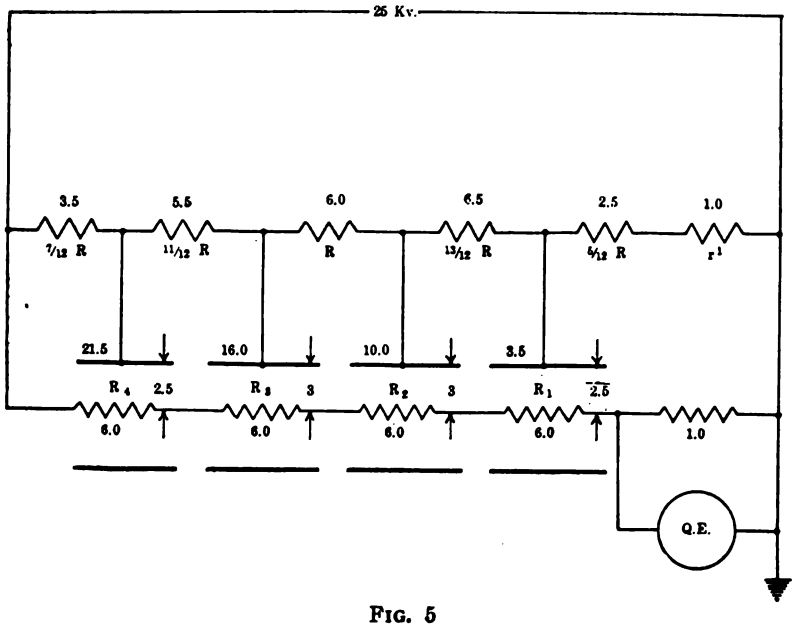

FIG. 5

potential between the earthed end (end of tube nearest earthed connection) of the tube and its protecting cylinder. The so-called telegraph formulas of Maxwell apply to a cable of this construction, and, by solving them, it is possible to ascertain what this potential difference should be.

The Manganini solution or the $\frac{2}{3}$ normal manitol, boric acid, calcium chlorid solution was used as the electrolyte. According to Maltby[1] this solution contains:

manitol	121.1 grams per liter
boric acid	41.2 grams per liter
calcium chlorid	0.06 grams per liter.

1. Maltby, *Zeitschrift. f. Ph. Ch.*, 18, S. 133, 1895.

To this solution I added one part of distilled water. Under these conditions the solution has a conductivity of about 0.00044 and between the limits 17 deg. and 24 deg. cent. the change in the resistance is less than 1/10 of one per cent.

The electrodes were of platinum and were plated with spongy (black) platinum in order to reduce the polarization to a minimum. The phase displacement due to the polarization was measured and found to be about two seconds of arc at a frequency of 50 cycles and with a current density of from 0.3 to 2.0 milliamperes per sq. cm. of electrode surface.

The resistance set which I built consisted of four resistance units. The set has two circuits, a main circuit, which consists of four resistance units, and a secondary circuit, which supplies the metal cylinders that protect the resistance units with voltage. Nine tubes in all were used, four in the main and five in the secondary circuit.

In Fig. 5 it has been assumed that a voltage of 25 kv. is being measured. The main circuit, which contains the four resistance units and a resistance r across which the quadrant electrometer is connected, is shown at the bottom part of the figure. The 25 kv. is supposed to be divided in this circuit as follows:

In the resistance r there is a voltage drop	$v = 1$ kv.
" " " unit R_1 there is a voltage drop	$V_1 = 6$ kv.
" " " " R_2 " " " " "	$V_2 = 6$ kv.
" " " " R_3 " " " " "	$V_3 = 6$ kv.
" " " " R_4 " " " " "	$V_4 = 6$ kv.

The total voltage in the main circuit is $v + V_1 + V_2 + V_3 V_4 = 25$ kv. The metal cylinders which protect the resistance units and give them a definite capacity are shown by the heavy black lines. The secondary circuit which supplies the proper potentials to these cylinders is seen in the upper part of the figure. In order to provide the correct potentials the resistances in the secondary must be of different sizes. In the secondary circuit the voltage is divided as follows:

In the resistance r' there is a voltage drop of	1.0 kv.
" " " 5/12 R there is a voltage drop of	2.5 kv.
" " " 13/12 R " " " " " "	6.5 kv.
" " " R " " " " " "	6.0 kv.
" " " 11/12 R " " " " " "	5.5 kv.
" " " 7/12 R " " " " " "	3.5 kv.
The total voltage in the secondary circuit is	25.0 kv.

The potential differences between the tubes in the main circuit and their protecting cylinders are also shown in the figure. There are, for the end resistance units R_1 and R_n (in this case R_4), 5/12 of the voltage drop per resistance unit or 2.5 kv.; for all other resistances R_2, R_3, . . . , $\frac{1}{2}$ of the voltage drop per unit or 3.0 kv. The tubes or resistance units in the main circuit are

all of the same size and have been designated by the letter R. The tubes in the secondary circuit are of various sizes, which have been given in terms of R, thus: 5/12 R, 7/12 R, etc.

With this set it is possible to measure voltages as high as 27,000 volts with all four resistance units in the main circuit, but for lower voltages it is advantageous to use fewer tubes. I should recommend the following combinations of the resistance units:

Up to 6000 volts, one resistance unit, and, in the secondary circuit, resistances 5/12 R and 7/12 R, and $r = r'$.

From 6000 to 12,000 volts, two resistance units, and, in the secondary circuit, resistances 5/12 R, R and 7/12 R, and $r = r'$.

From 12,000 to 18,000 volts, three resistance units, and, in the secondary circuit, resistances 5/12 R, 13/12 R, 11/12 R and 7/12 R, and $r = r'$.

From 18,000 to 24,000 volts, four resistance units, and the entire secondary circuit, and $r = r'$.

For voltages much above 24,000 volts, extra resistance units must be added to the main circuit, and also in the secondary circuit an extra resistance R for each unit added to the main circuit.

Tests of the resistance set that was built from resistances wound with manganin wire were made[2] at the Reichsanstalt, Germany, and I carried out a series of tests[3] on the set that I built with the electrolytic resistances. These tests showed that the theoretical assumptions were correct and that the voltages measured were accurate to within ½ of one per cent.

It should be possible to use eight of these electrolytic resistances in series without over-stepping the theoretical limits for accuracy, thereby increasing the range of a single set to approximately 50,000 volts. With two such sets connected in series and grounded at the junction point, voltages of twice that magnitude could be handled. The use of the electrolytic resistances for high-frequency work possesses the advantage that they are free from self-induction, and with increasing frequency the polarization would disappear entirely.

Three voltage transformers were tested for the constancy of the ratio of transformation. The primary voltage was measured in each case by a Weston a-c., d-c. voltmeter. The ratio of transformation was found in every case to be constant to within one per cent from about half voltage to full rated voltage of the transformer. For low voltages, however, the ratio of transformation gave results that were in some cases as much as four per cent too high, the error decreasing more or less gradually as half rated voltage was approached. Therefore investigators should be very careful when making high-voltage tests not to rely too much upon the ratio of transformation.

2. Orlich and Schultze, *Archiv. f. Elek.*, 1, S. 1 and 88, 1912.

3. Kouwenhoven, *Washington Univ. Studies*, Vol. 1, p. 143, 1914.

Harris J. Ryan (by letter): Replying to Mr. Fortescue's questions: The high-frequency driving voltage of the arc was multiplied about one hundred times by resonance. The impressed voltage of the arc having an irregular wave form was consumed in the first few turns of the outer helices. Thus in a given case the potential to neutral of the sixth turn from either arc terminal would, on test, be found at low (almost zero) alternating potential. On either side of this turn the potential would be found to rise regularly. By theory, under these circumstances, it is difficult to understand how the high-potential wave form can have departed appreciably from that of the true sine wave. The cyclograph traced a quadrature combination of current and potential waves. The result was a true ellipse with no evidence of the presence of harmonics. In regard to the use of isolated spheres made necessary in the method devised to eliminate harmonics in the high-frequency high voltage: The case is not one of actual isolation, as assumed by Mr. Fortescue. The arc was supplied with current from two 600-volt direct-current generators connected in series with their neutral grounded. Furthermore, the oscillating circuit would fail utterly to operate unless both sides of the circuit were nicely balanced, developing substantially equal voltages.

We are not asking that our results be accepted as final. The art of generating and handling high-frequency high voltages is undeveloped as yet. It would not be reasonable to expect final results at this time even with the high-frequency alternator driven at *constant speed* as suggested by one speaker.

In his closing remarks Mr. Peek has accounted for the erratic behavior of the sphere gap voltmeter, cited by Mr. Chubb, when in action above 320,000 volts. He presents his method for eliminating such behavior. Closely related hereto are two experiences encountered in our work.

Regarding the first experience—we have mentioned in our paper that we could not use the condenser voltmeter to measure voltages beyond 50,000. Discharges through the four-inch (aggregate) gap in the two pairs of 7- and 11-inch concentric cylinders, six feet in length, would occur in an erratic fashion at voltages above 53,000. In planning this apparatus we had concluded from the results of Fortescue and others that such discharges should not take place at voltages below 165,000. We expected, therefore, to use the cylinders and instruments with safety for authenticating voltages as high as 125,000, *i.e.*, to the limit of the high-frequency voltage capacity of our equipment. Since the completion of our paper we arranged to subject these concentric cylinders to 60-cycle voltage. In so doing all essentials were made to correspond to those present in the high-frequency work, *i.e.*, the neutral of the single-phase 60-cycle source was grounded, while the "neutral"-connected outer eleven-inch cylinders were left isolated. They were shunted with the sphere gap set to stop any possible transient

over-voltages. Thus arranged, the sphere gap acted in agreement with voltages determined by transformer ratios and voltmeter. The concentric cylinders discharged at voltages all the way from 80 to 100 kilovolts. The lower and higher values occurred correspondingly when the voltage was raised slowly and rapidly. Using one pair of cylinders only, the outer one grounded, the discharge voltages ranged from 40 to 50 kilovolts. The equipment was then dismantled and the seven-inch cylinders were mounted in a cross and separated so as to form a gap between them of three inches; so arranged, 157 kilovolts were required to discharge between them. It seems to us that the free ionization in this case is present in the tarnished and dust-coated surfaces of these cylinders, and from there is worked into a line-up forming local corona through the two-inch zones of well-protected air under the forces of the electric field, thereby starting a disturbance that finishes in a heavy spark, *i.e.*, in a transient discharge, or otherwise, in an actual arcing short circuit. The discharging voltages were lower when the tests were started and gradually rose as the reapplications of high voltage were continued, indicating a sort of cleaning-up process.

In the second experience it was found that when using a seven-inch sphere gap of two inches or thereabouts, the high-frequency discharge would take place by the shortest path between the spheres at 93 kilovolts. When a lower voltage was applied and a slight disturbance created at one of the surfaces of the opposing spheres by touching it with a piece of hard rubber, a discharge immediately occurred. It would be started by a spark of charging current from the sphere to the hard rubber. Discharges, a foot and more in length, would be made to pass from the rearward surface of one sphere to the corresponding rearward surface of the other at 85 kilovolts, in the general direction of the lines of force, by bringing to the surface of the sphere from the rear a three-quarter-inch hard rubber rod.

Mr. Mahood recommends that the Poulsen oscillating arc used for sphere gap voltmeter calibration be replaced by "the best oscillating arcs constructed and specially designed for stability purposes" giving only "*two per cent* variation in amplitude at 133,000 cycles." Such arcs, while steady, are entirely lacking in duty capacity. A maximum of 1500 kilovolt-amperes of reactive power was employed for the high-frequency sphere gap work, while a few hundred volt-amperes suffice for standardizing radio receiving apparatus—accomplished readily enough with such light-duty constant arcs. Mr. Mahood confuses the duties of the ammeters in the circuit of the concentric condensers and the potential cyclograph. The former and not the latter read the r.m.s. of the existing potential. The cyclograph gave a continuous vision of the procession of potential oscillations in instantaneous detail. The same speaker makes the suggestion that pure undamped waves were not used in our work because under his own assumption the decrement (for

damped waves) was 0.02. The suggestion can not be taken seriously. The cathode ray cyclograph established beyond all reasonable doubt that the oscillating potentials were formed continuously and undamped. These are merely efforts to find near-by evidence to support the theory that the action of the sphere gap voltmeter is independent of the frequency of the applied voltage.

The sphere gap discharge voltages were not altered by the use of the safety resistance rods at 123,000 cycles. They were abandoned at higher frequencies, as stated in the paper, because the resistances that would limit sufficiently the rush of continuous current that followed a discharge across the sphere gaps would consume an undue amount of power, limiting or preventing the generation of voltage in the oscillating circuit.

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